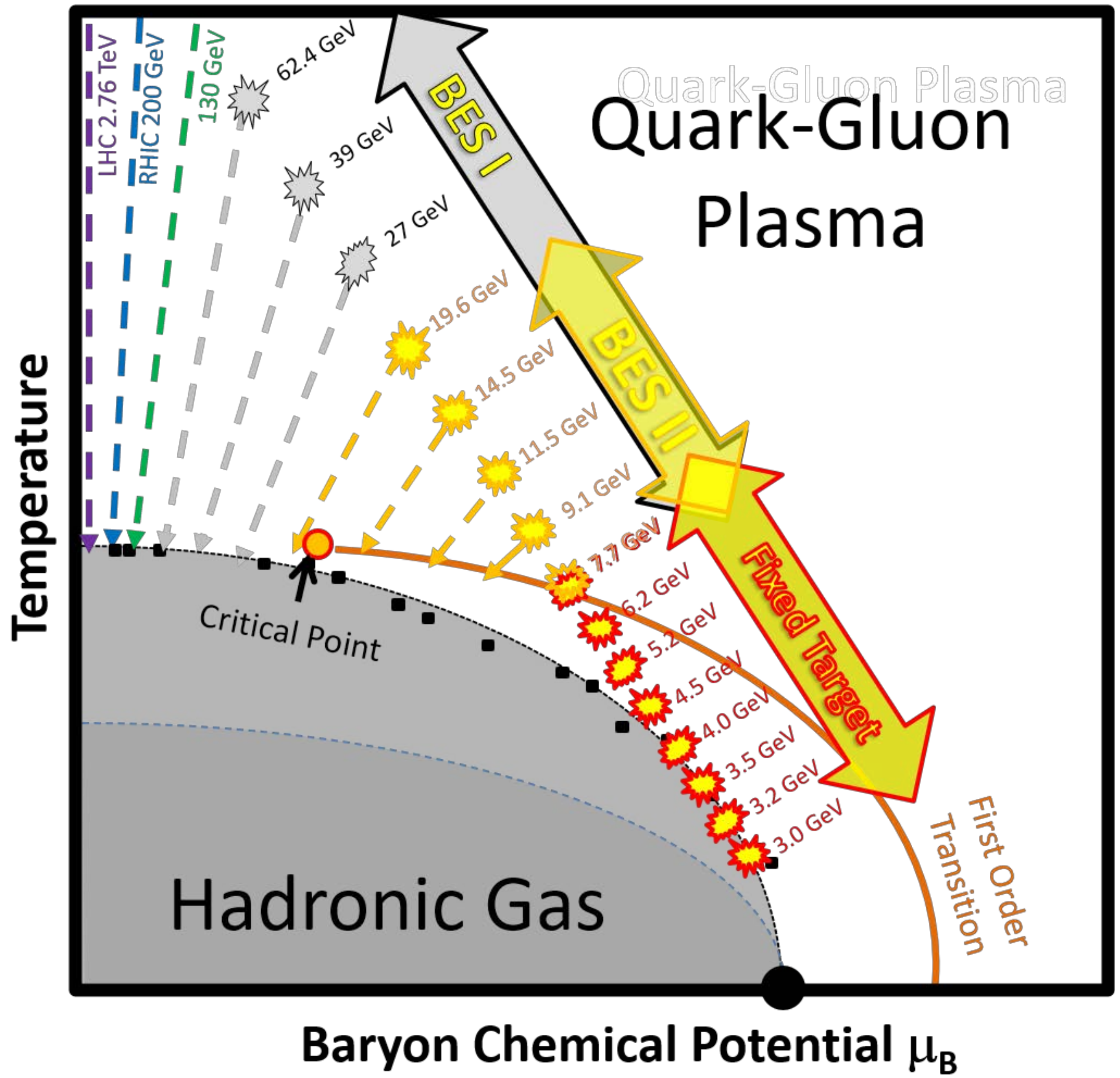
RHIC Beam Energy Scan and Vorticity

TCHoU meeting

2023/6/27

Kosuke Okubo

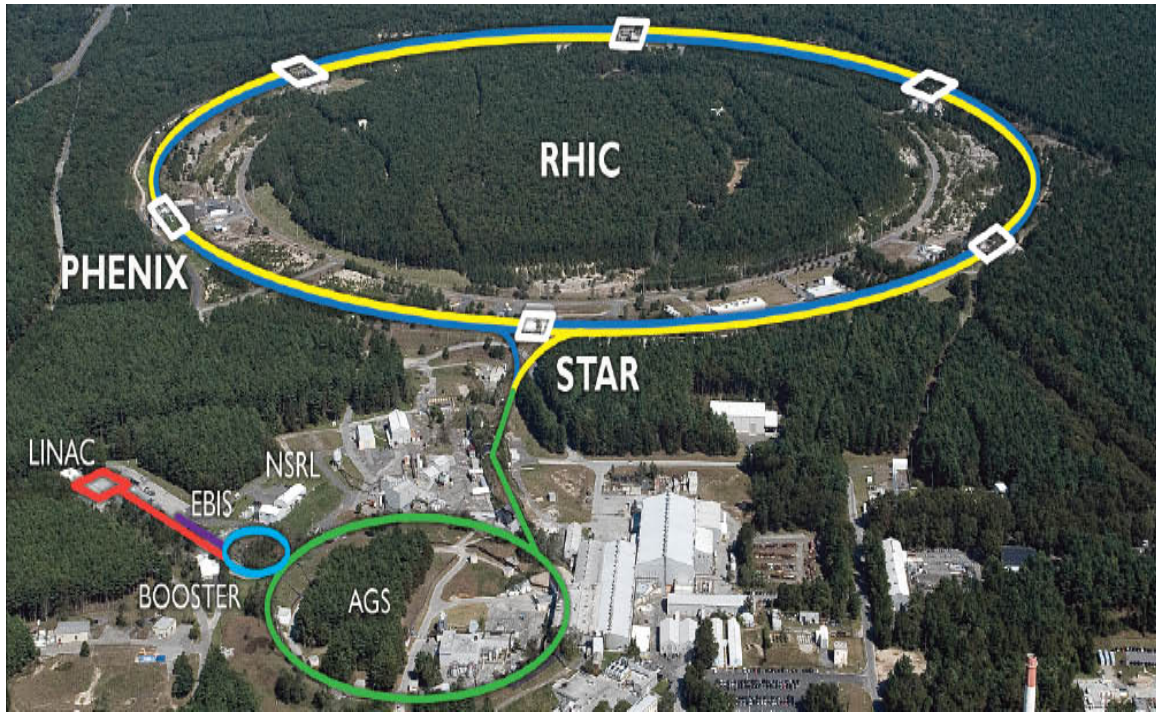
Heavy ion collisions experiment



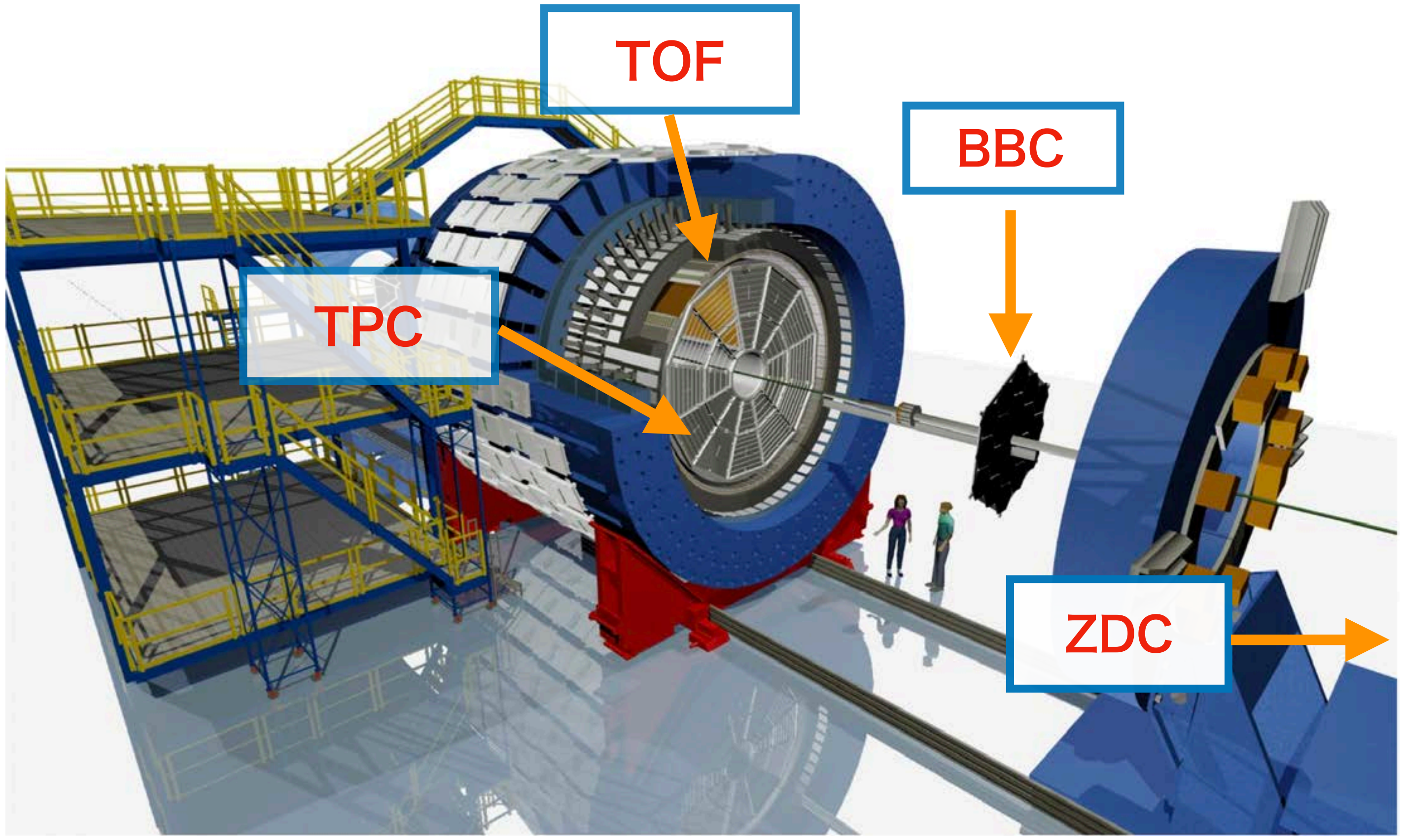
- Understand the properties of quark-gluon plasma(QGP)
- Map out QCD phase diagram
- Beam energy scan program

RHIC-STAR experiment

Relativistic Heavy Ion Collider (RHIC)



Solenoidal Tracker At RHIC (STAR)



- Brookhaven National Lab. (NY)
- $\sqrt{s_{\rm NN}}$ = 7.7 - 200 GeV for A+A

  p+p, p+Au, Au+Au, Cu+Cu,Cu+Au…

- **Time Projection Chamber (TPC)**
  - Main tracking detector, $|\eta|<1.0$, full azimuth
- **Time-Of-Flight (TOF)**
  - Particle identification, $|\eta|<0.9$, full azimuth
- **Beam-Beam Counters (BBC)**
  - Event plane reconstruction , $3.3<|\eta|<5.0$
- **Zero Degree Calorimeters (ZDC)**
  - Event plane reconstruction using spectator neutrons, $|\eta|>6.3$

Vorticity and magnetic field

✦In non-central collisions…

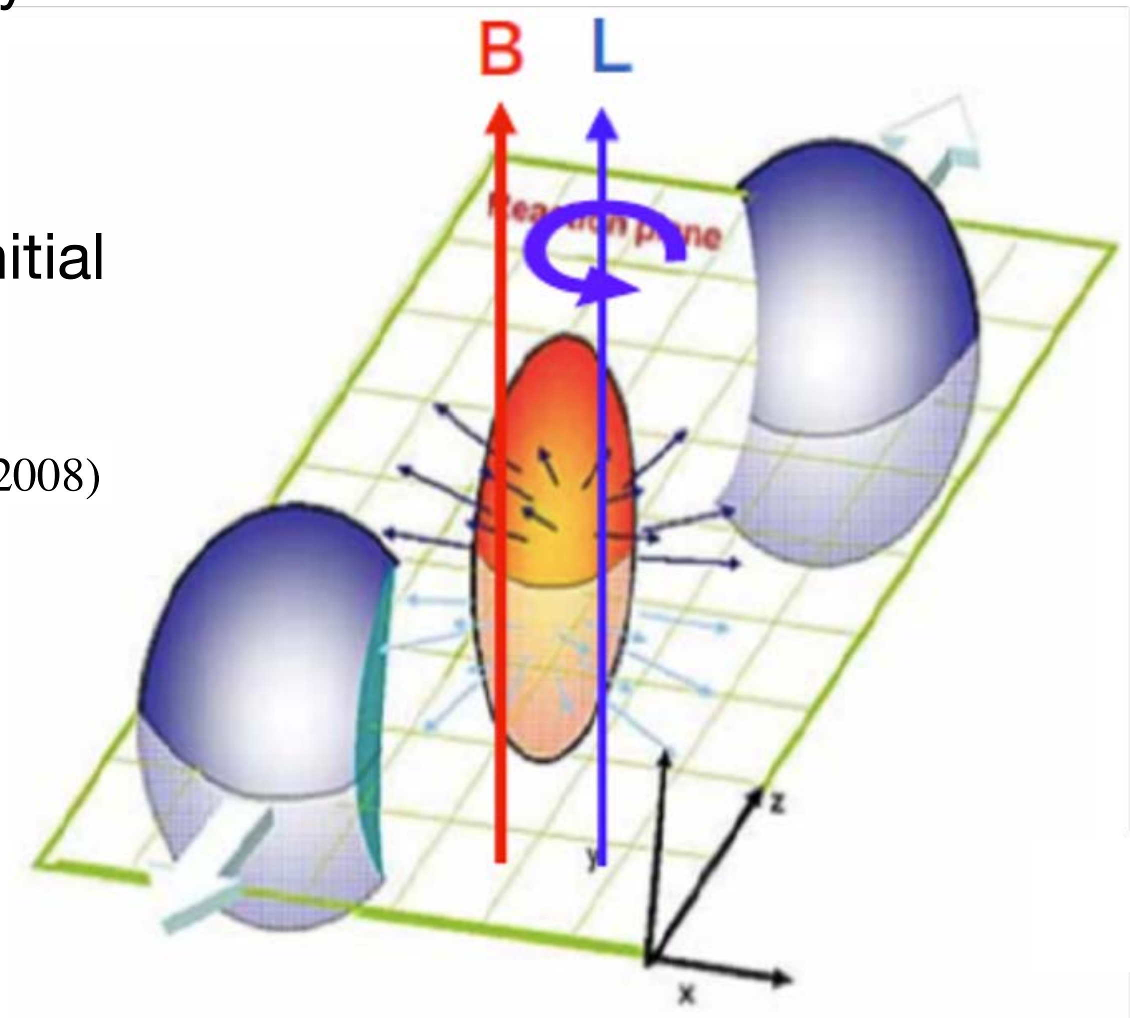
- The created matter should exhibit strong vorticity.

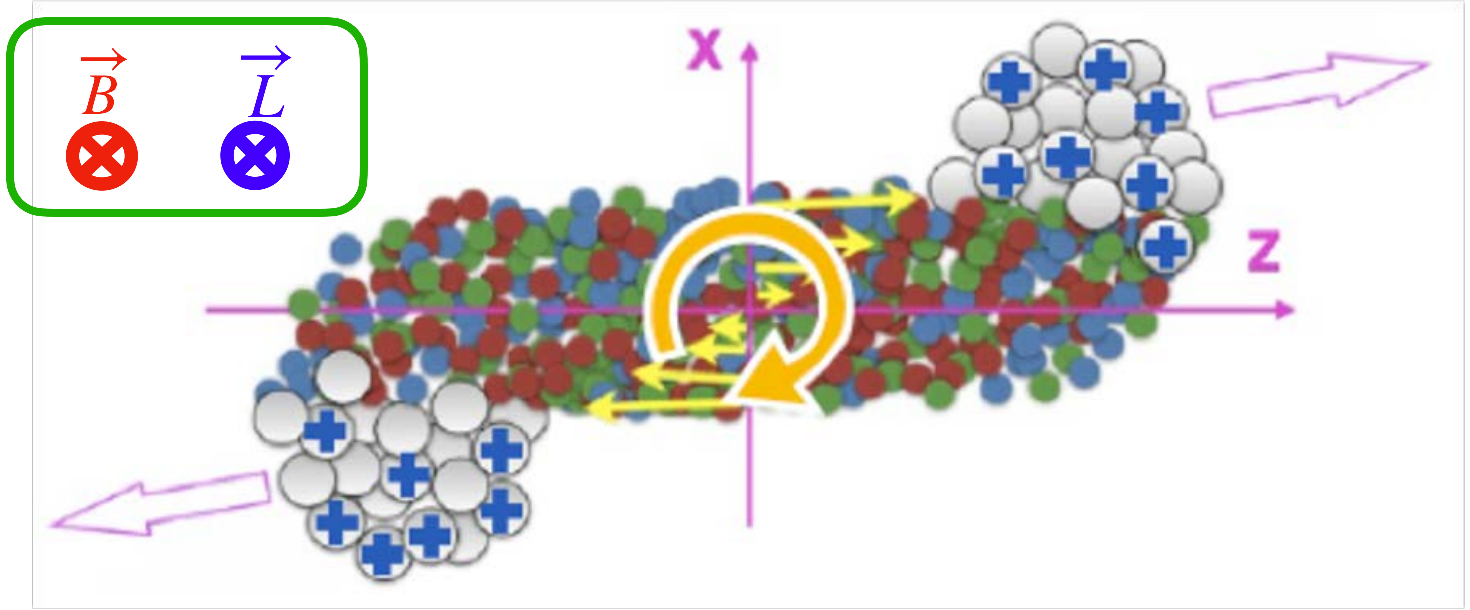
  -Z.-T.Liang and X.-N. Wang, PRL94, 102301

- The strong magnetic field would appear in the initial state.

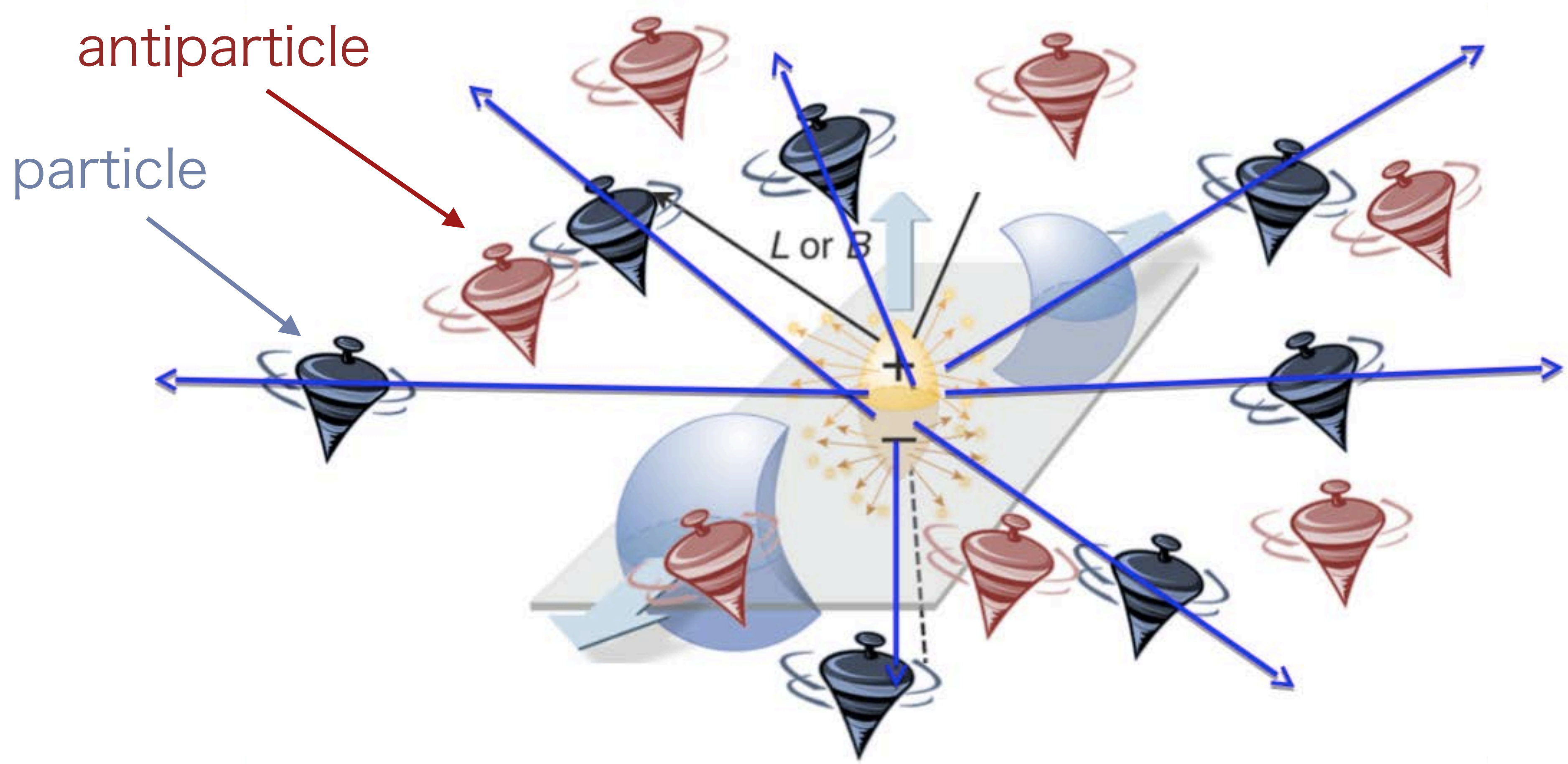
  -D. Kharzeev, L. McLerran, and H. Warring, Nucl.Phys.A803, 227 (2008)

  -McLerran and Skokov, Nucl. Phys. A929, 184 (2014)





Global polarization



- Large orbital angular momentum transfers to the spin degrees of freedom:
  - **Quarks and anti-quarks' spins are aligned with the angular momentum.**
- Spin alignment by magnetic field:
  - **Quarks and anti-quarks get aligned in the opposite direction due to the opposite signs of their magnetic moments.**

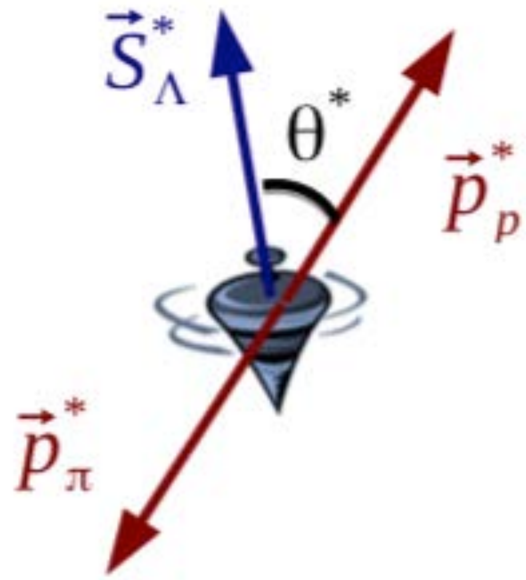
How to measure the global polarization?

✦Parity-violating decay of hyperon

- Daughter proton preferentially decays along the Λ's spin (opposite for anti-Λ).

$$\Lambda \rightarrow p + \pi^- \quad \text{(BR:63.9\%, } c\tau\text{~7.9cm)}$$

- Polarization can be measured via the distribution of the azimuthal angle of the daughter proton (in the hyperon rest frame).



✦Projection onto the transverse plane

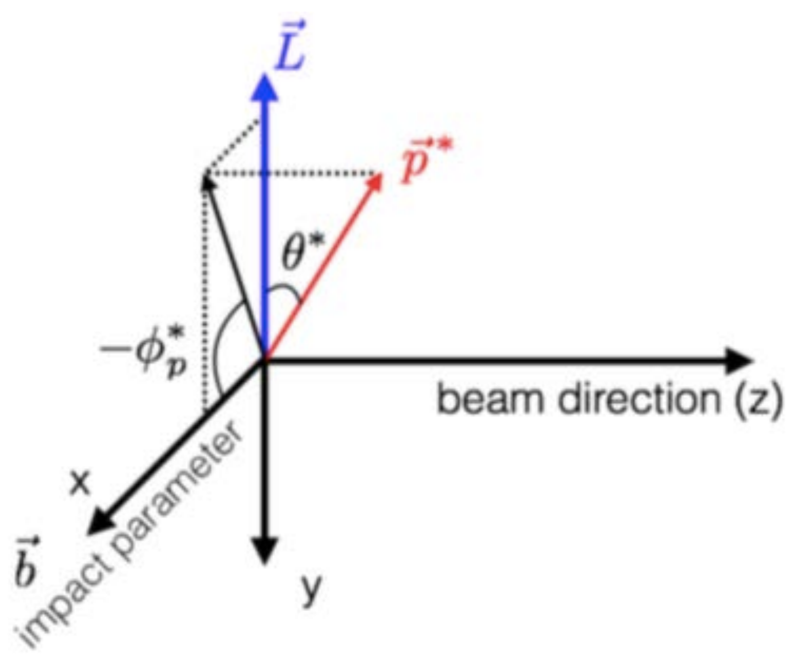
$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{Res(\Psi_1)}$$

- STAR, PRC76, 024915(2007)

α_H : decay parameter ($\alpha_\Lambda = 0.732 \pm 0.014$)

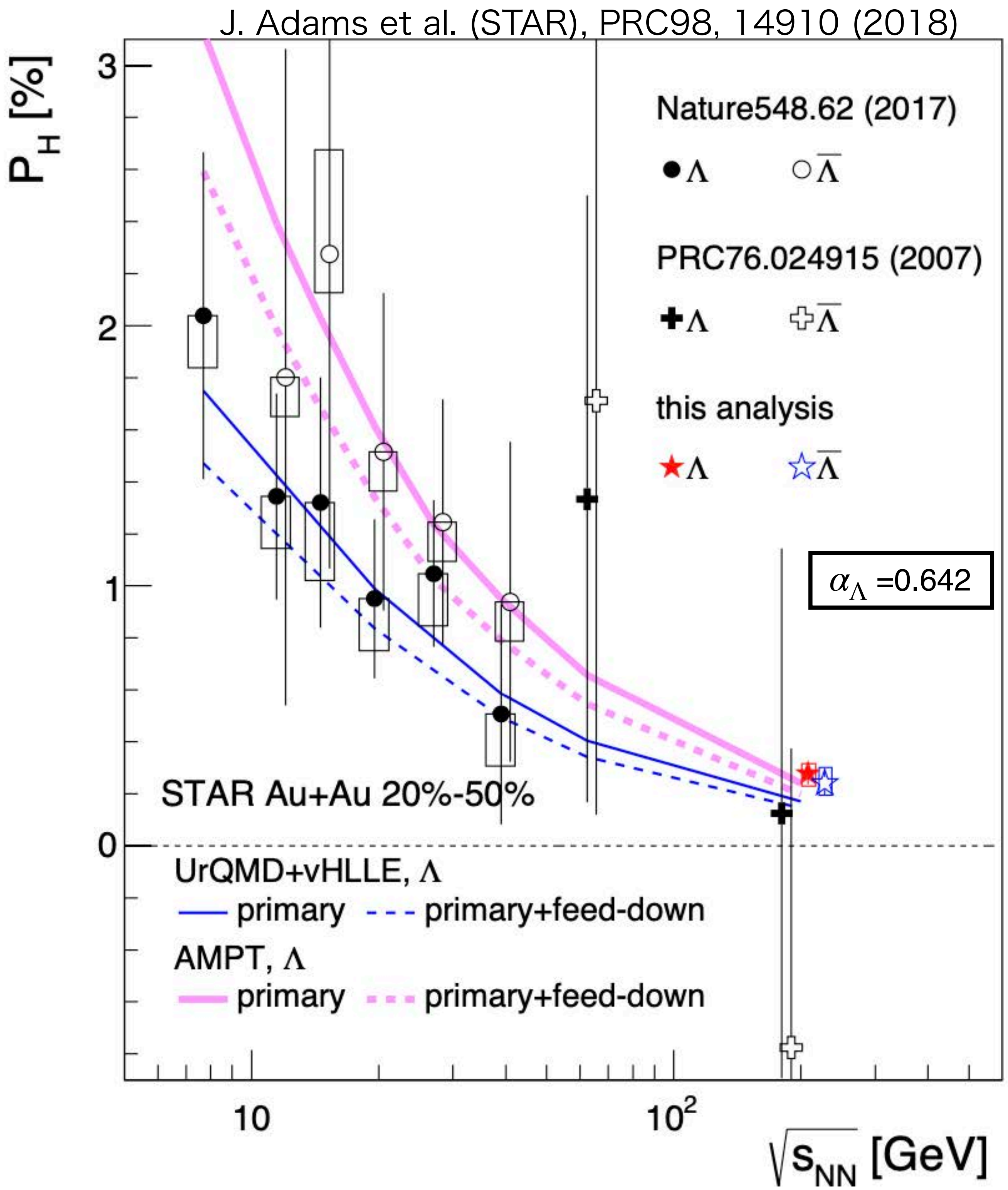
Ψ_1 : 1^{st}-order event plane

ϕ_p^* : azimuthal angle of the daughter proton in the Λ's rest frame



P.A. Zyla et al. (PDG), Prog. Theor. Exp. Phys.2020, 083C01 (2020).

Collision energy dependence of P_H



- Positive polarization signals are observed.

Becattini, Karpenko, Lisa, Upsal, and Voloshin,PRC95.054902 (2017)

$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T}$$

$$\omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{21}s^{-1}$$

μ_Λ : magnetic moment

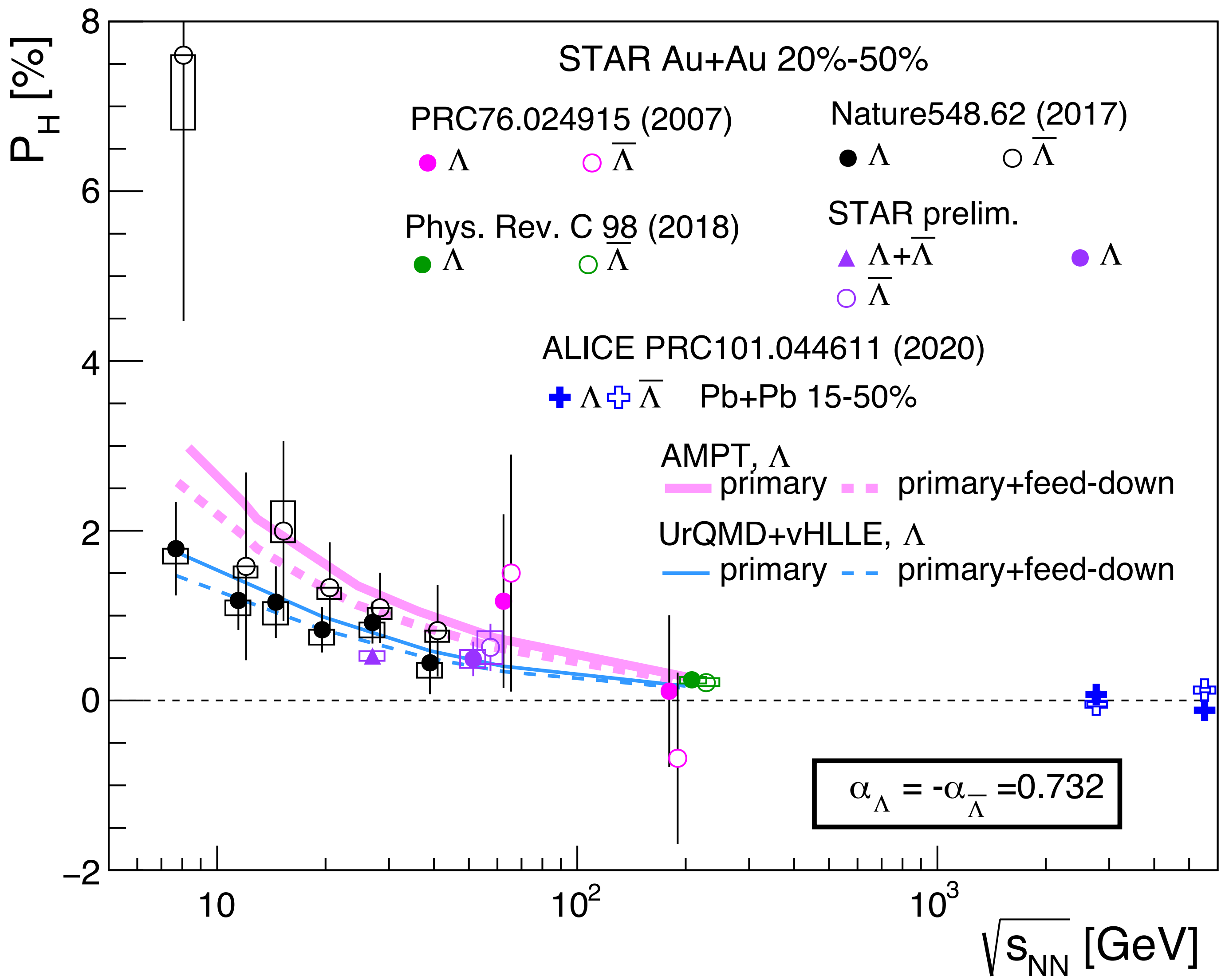
T : temperature at thermal equilibrium(=160 MeV)

- Polarization increases with decreasing collision energy.

- No significant difference between Λ and anti-Λ.

Collision energy dependence of P_H

Global polarization of Λ hyperons in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV.



2.76 TeV

$$P_{\Lambda}(\%) = 0.08 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$

$$P_{\bar{\Lambda}}(\%) = -0.05 \pm 0.10(\text{stat.}) \pm 0.03(\text{syst.})$$

5.02 TeV

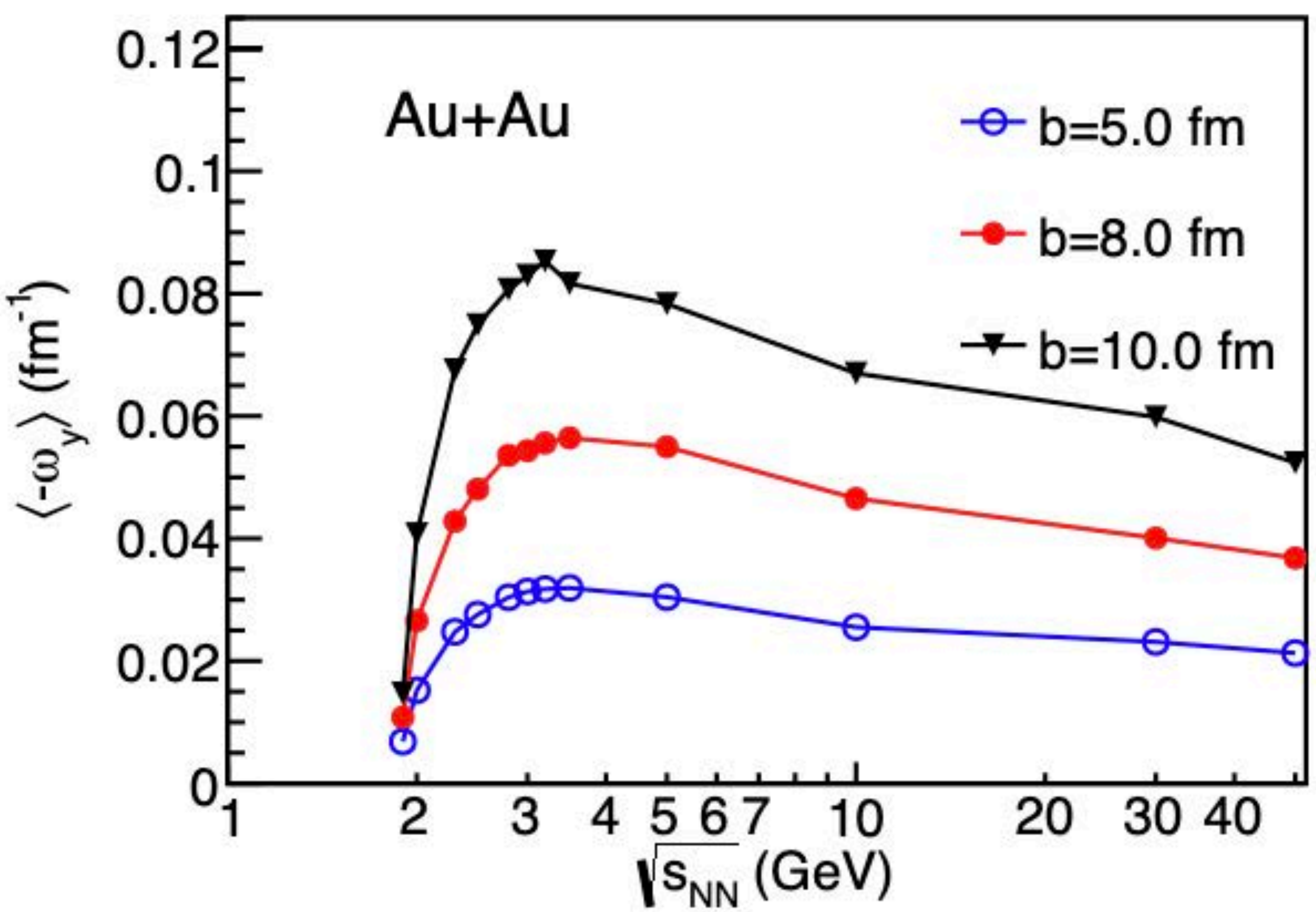
$$P_{\Lambda}(\%) = -0.13 \pm 0.11(\text{stat.}) \pm 0.04(\text{syst.})$$

$$P_{\bar{\Lambda}}(\%) = 0.14 \pm 0.12(\text{stat.}) \pm 0.03(\text{syst.})$$

✓Global polarization continue to decrease at higher energies.

Vorticity at low energy

X.-G. Deng et al., PRC101.064908 (2020)

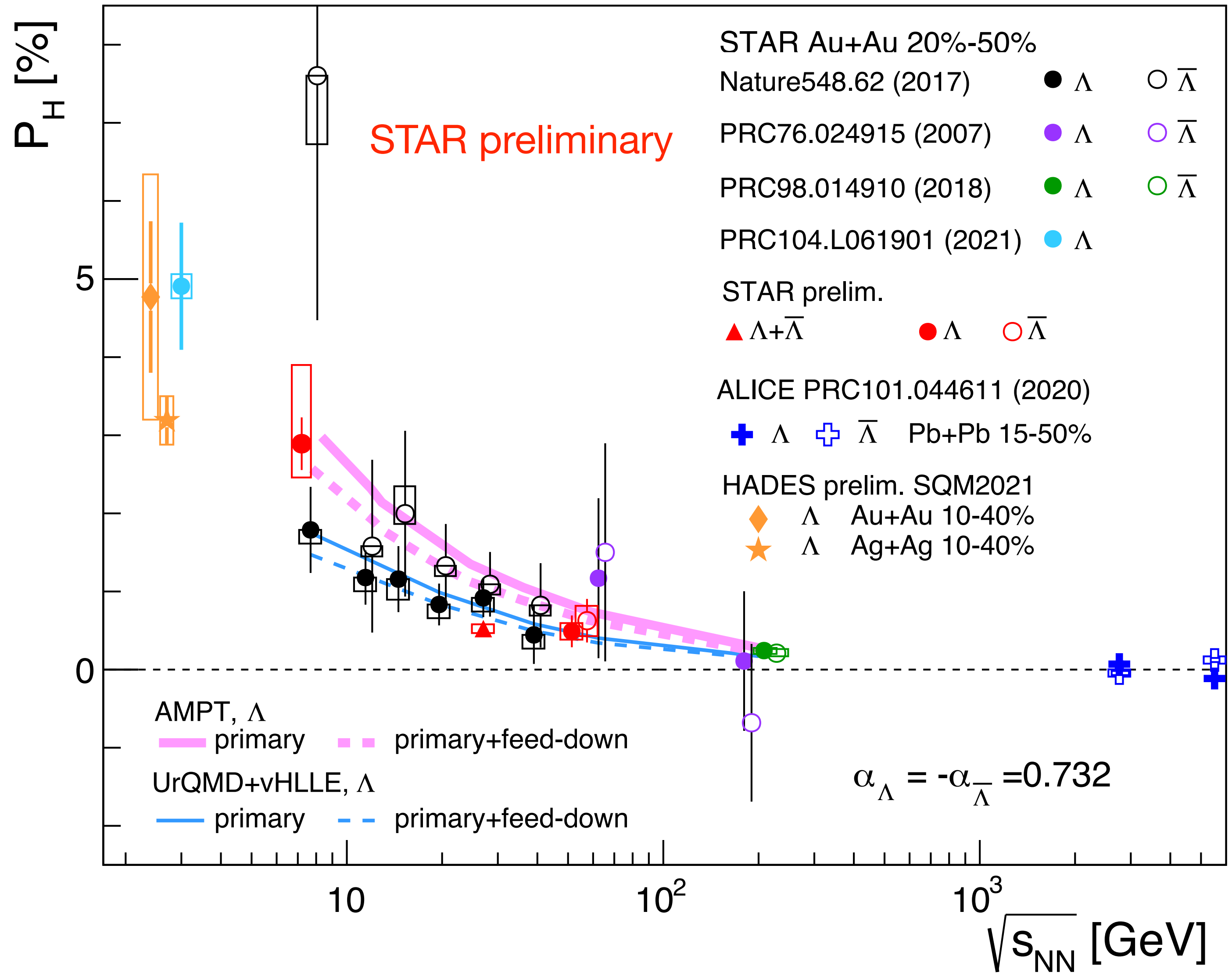


UrQMD model

- Angular momentum is the largest at 3 GeV.
- Vorticity disappears at $2m_N$ GeV.

➡Global polarization is expected to be the largest at $2m_N \approx 1.9 < \sqrt{s_{\mathrm{NN}}} < 7.7$ GeV.

Global polarization in low energies

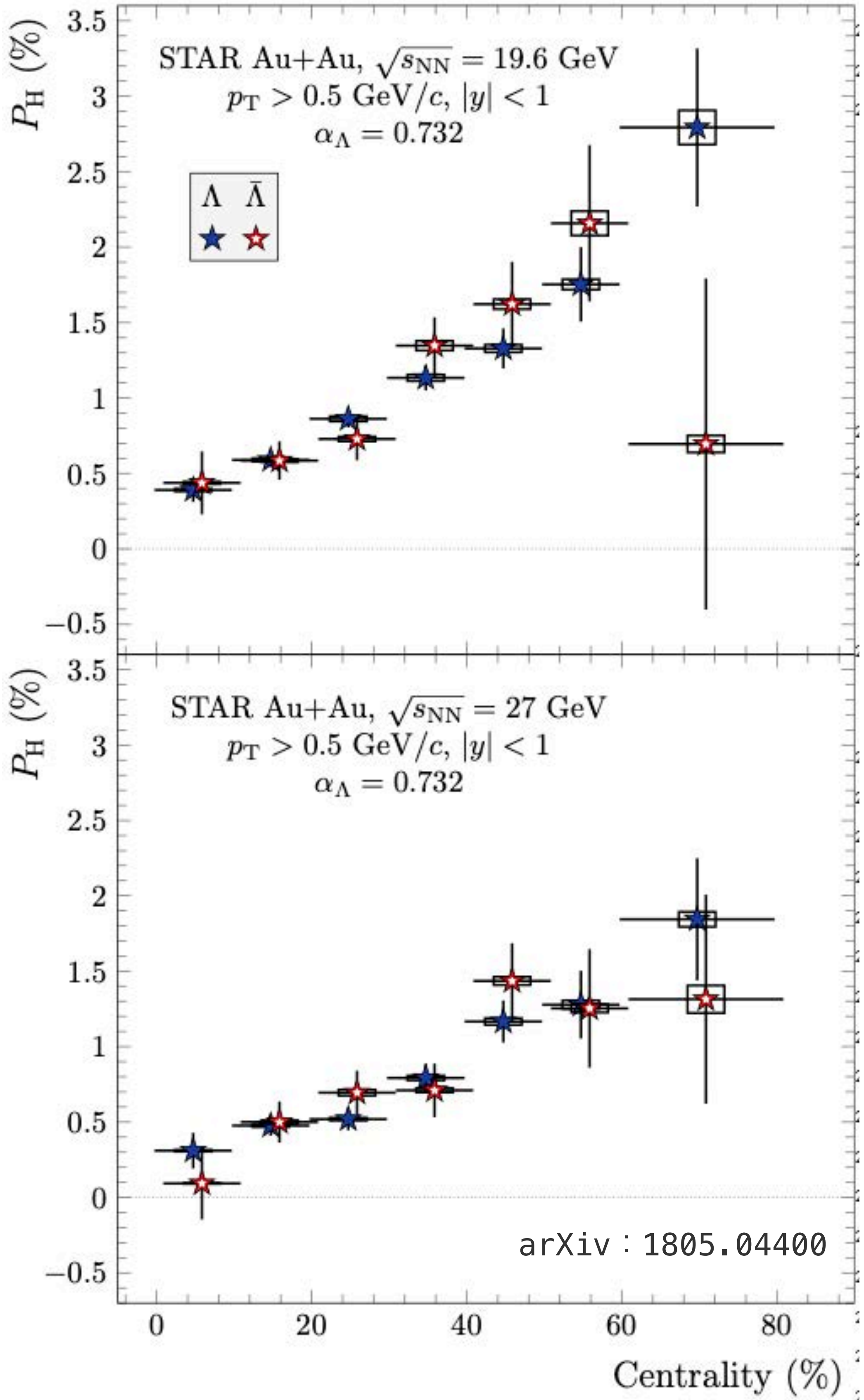


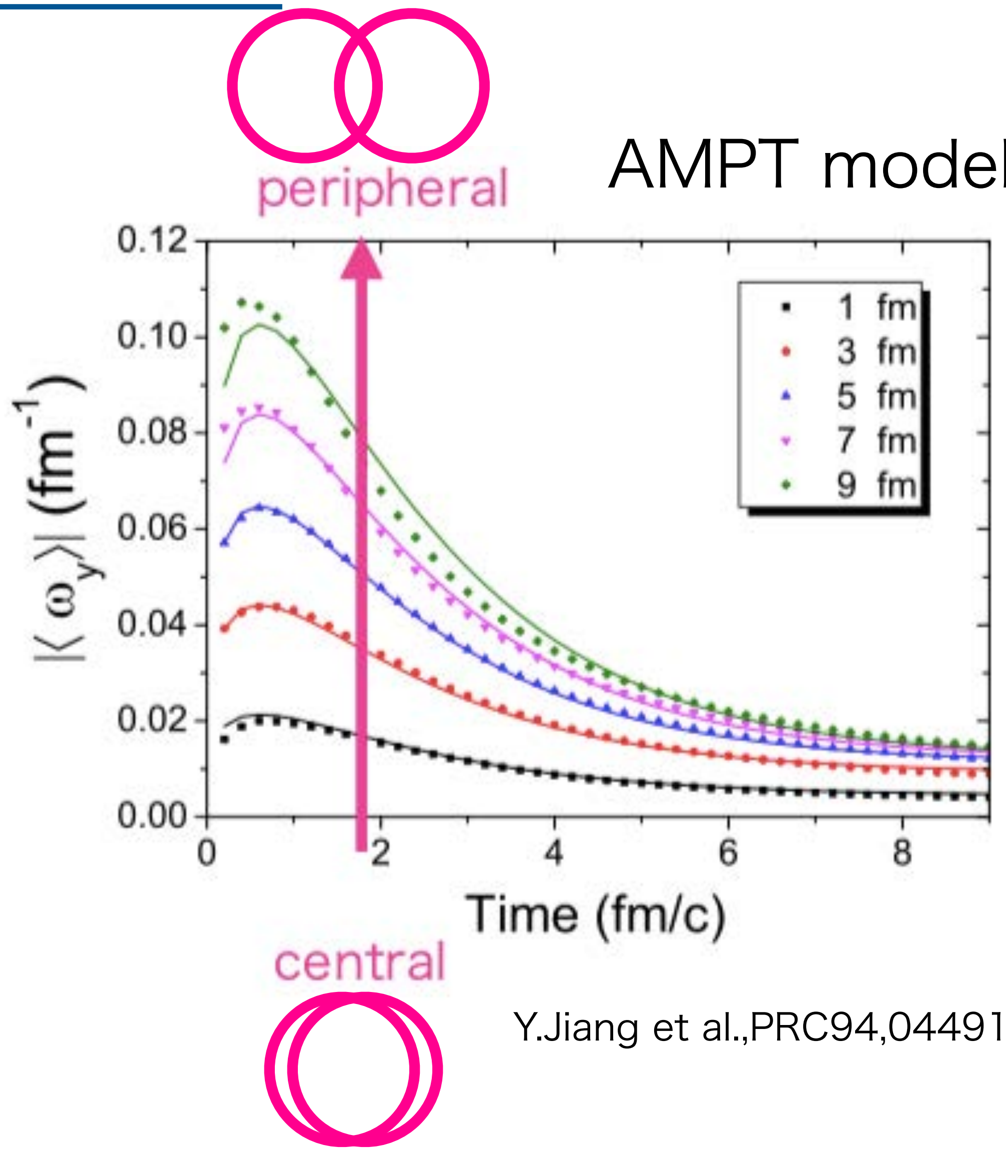
- HADES experiment has measured in Au+Au at 2.4 GeV and Ag+Ag at 2.55 GeV.

- STAR experiment has measured in Au+Au at 3.0, 7.2 GeV.

➡Global polarization increases with decreasing collision energy to 2.4 GeV.

Centrality dependence of P_H





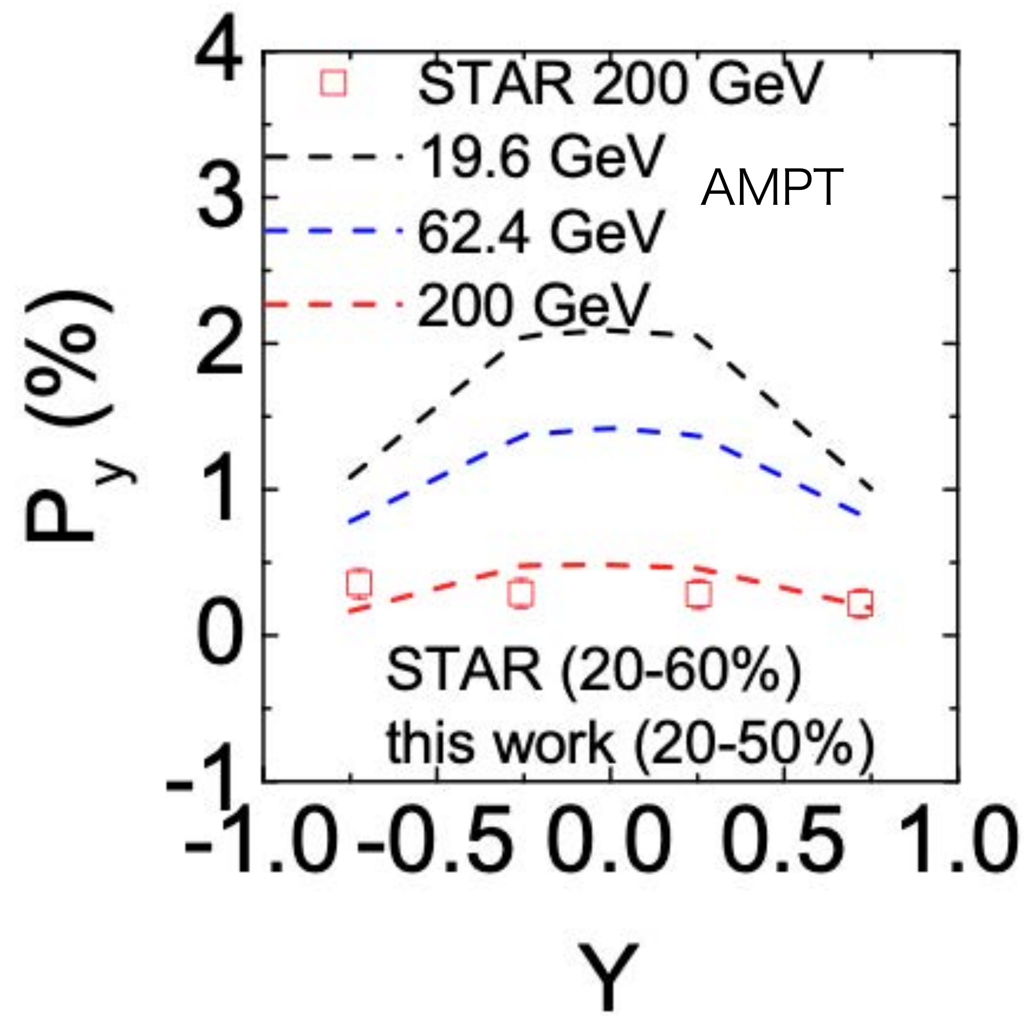
Y.Jiang et al.,PRC94,044910(2016)

- In most central collision, no initial angular momentum.
- **The polarization decrease in more central collisions.**

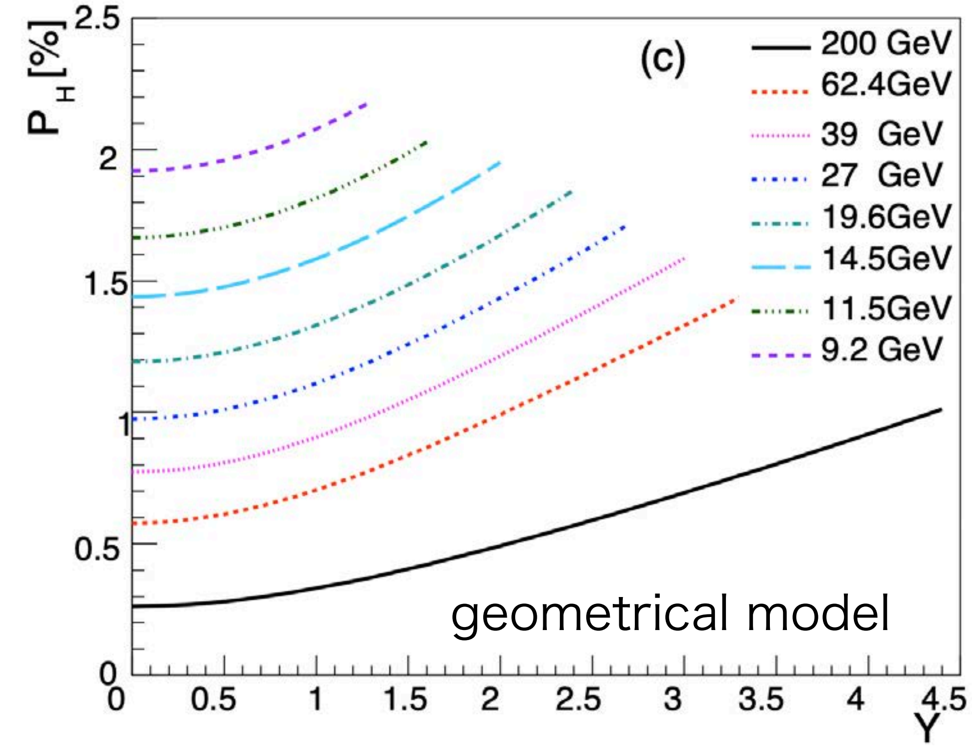
Rapidity dependence of P_H

- Polarization is expected to depend on rapidity but the prediction is different among the models.

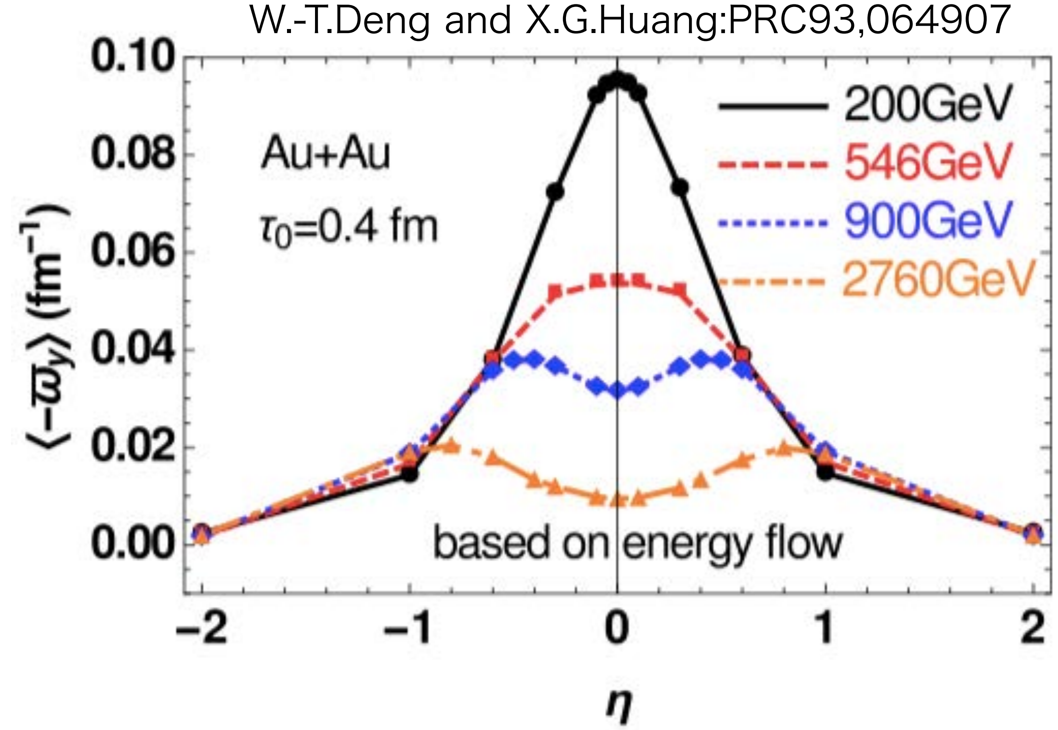
D.X.Wei, W.T.Deng and X.G.Huang, PRC99.014905 (2019)



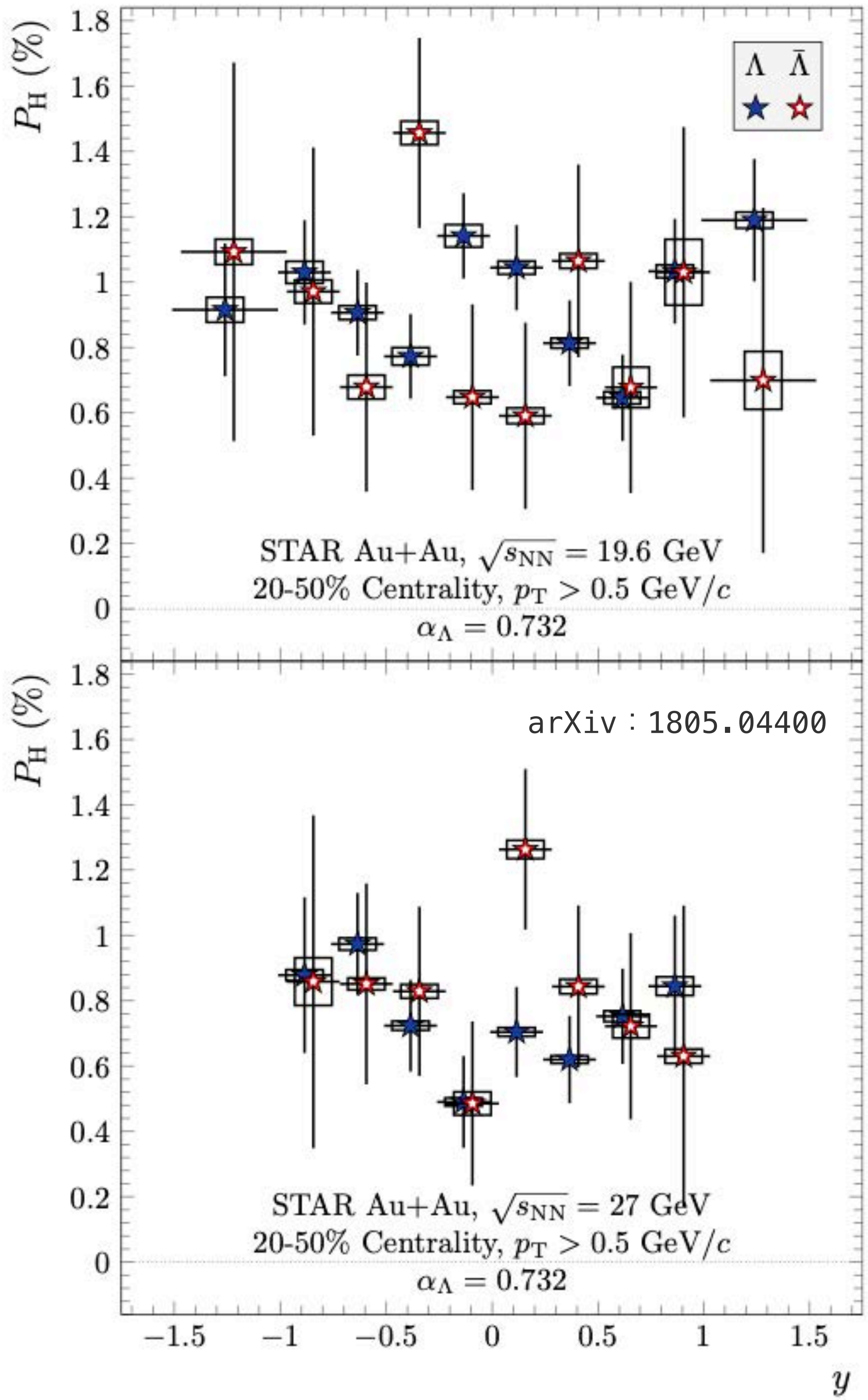
Z.T.Liang et al., Chin.Phys.C 45 (2021) 1, 014102



W.-T.Deng and X.G.Huang:PRC93,064907



Rapidity dependence of P_H



- **Polarization does not show significant rapidity dependence within acceptance.**

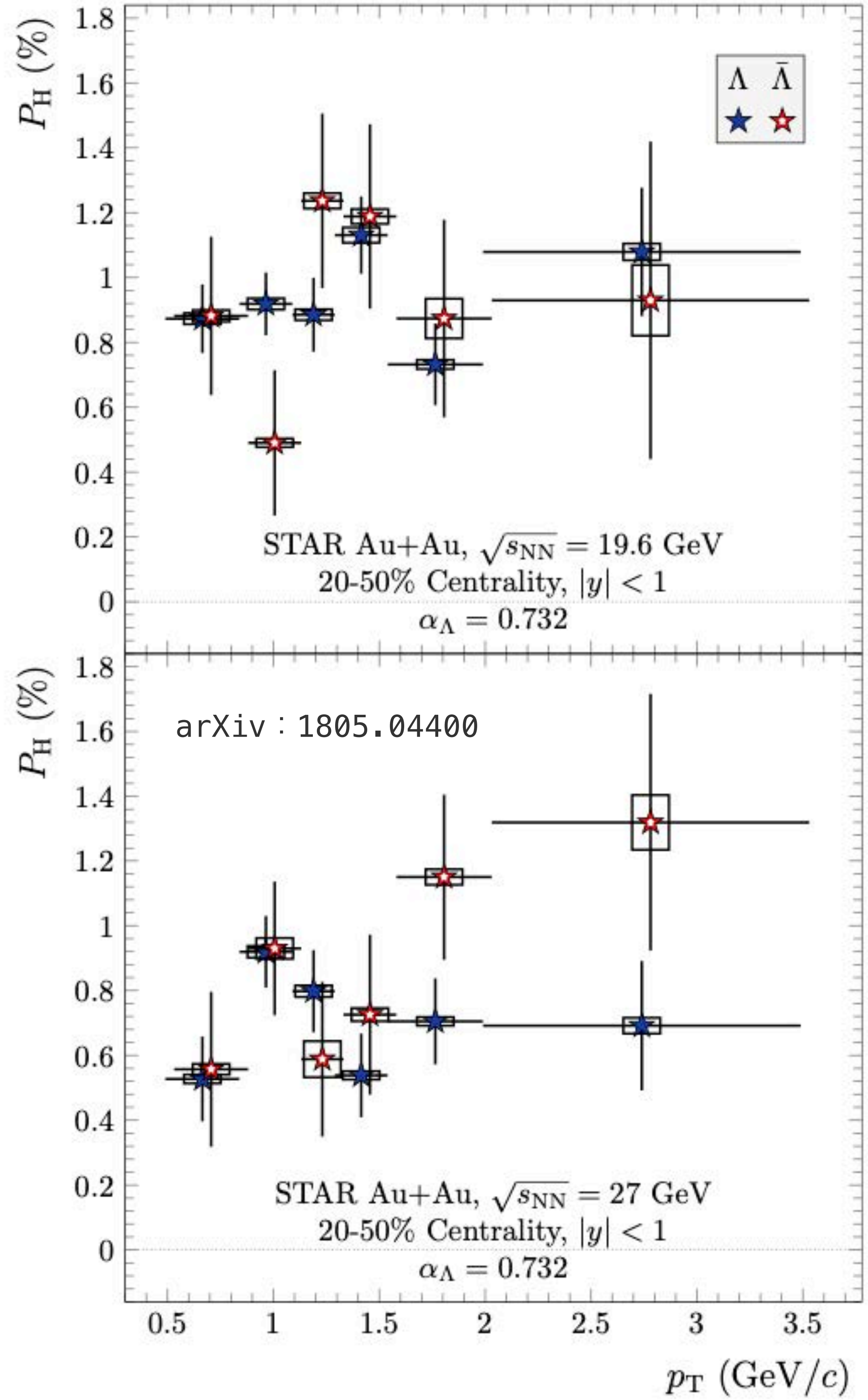
- Polarization in large rapidity region can be explored in the future forward upgrade.

Transverse momentum dependence of P_H

One might expect…

- Decrease at low p_T due to the smearing effect caused by scattering at the later stage of the collisions.
- Decrease at high p_T due to jet fragmentation.

No significant p_T dependence within uncertainties.



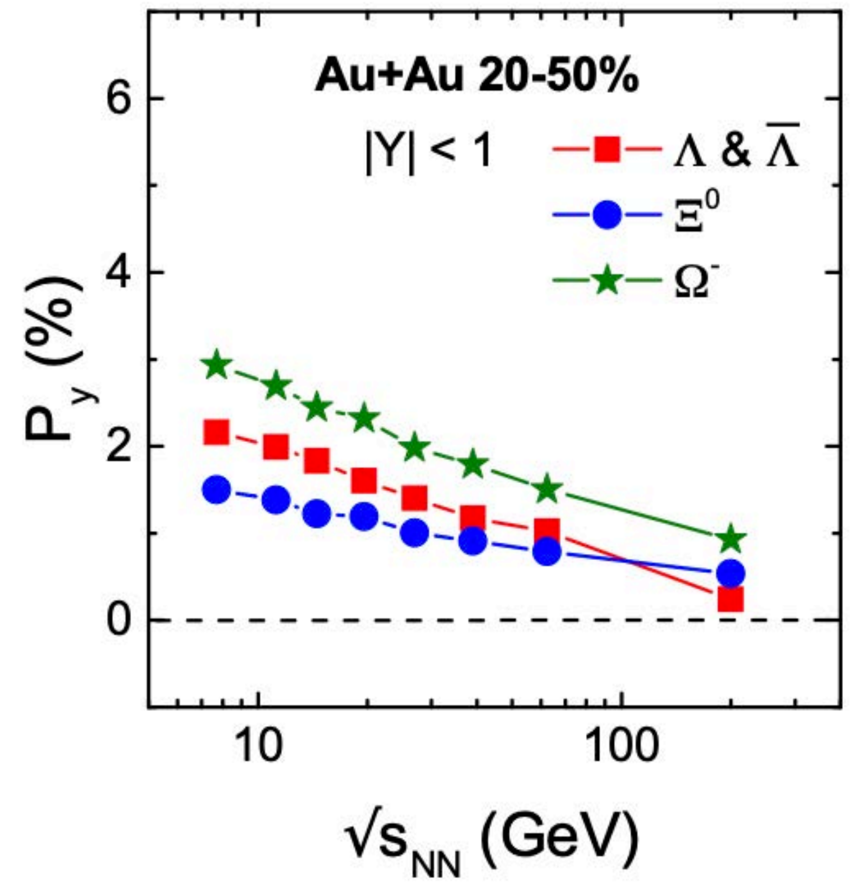
Global polarization of Ξ and Ω

P. A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

hyperon	decay mode	α_H	magnetic moment μ_H	spin
Λ (uds)	$\Lambda \to p\pi^-$ (BR: 63.9%)	0.732	-0.613	1/2
Ξ^- (dss)	$\Xi^- \to \Lambda\pi^-$ (BR: 99.9%)	-0.401	-0.6507	1/2
Ω^- (sss)	$\Omega^- \to \Lambda K^-$ (BR: 67.8%)	0.0157	-2.02	3/2

Global polarization measurement of the other particles.

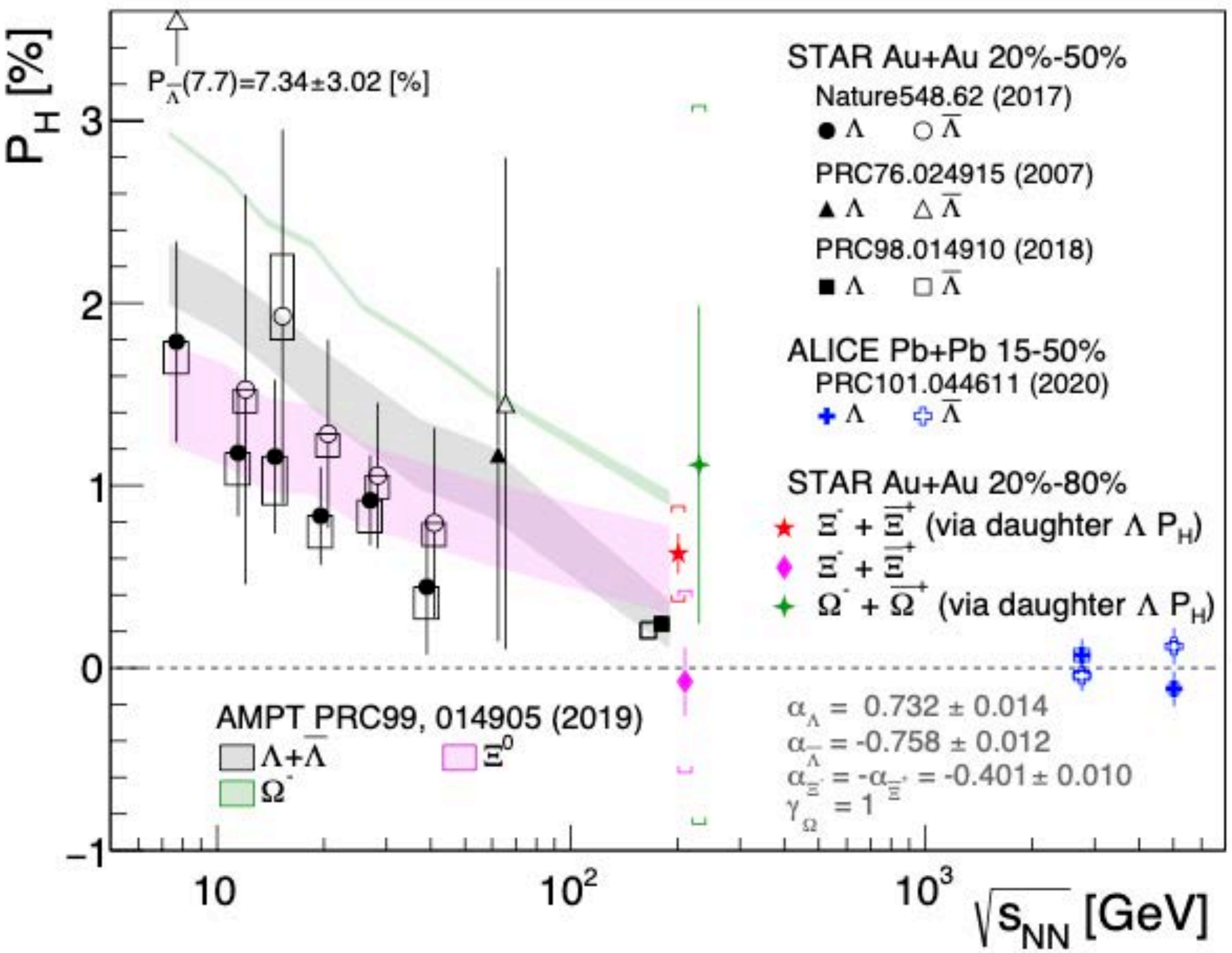
- Different spin and magnetic moments
- Less feed-down in Ξ and Ω compared to Λ
- Could be different freeze-out
- Different valence s-quarks
- Less statistics of Ξ and Ω compared to Λ



W.-T. Deng and X.-G. Huang, PRC93.064907 (2016)

Ξ and Ω polarization measurement at 200 GeV

J, Adam et al. (STAR), PRL126, 162301 (2021)



- Global polarization of Ξ and Ω in Au+Au collisions at 200 GeV

$$\langle P_\Lambda \rangle = 0.24 \pm 0.03(\text{stat.}) \pm 0.03(\text{syst.})\ [\%]$$

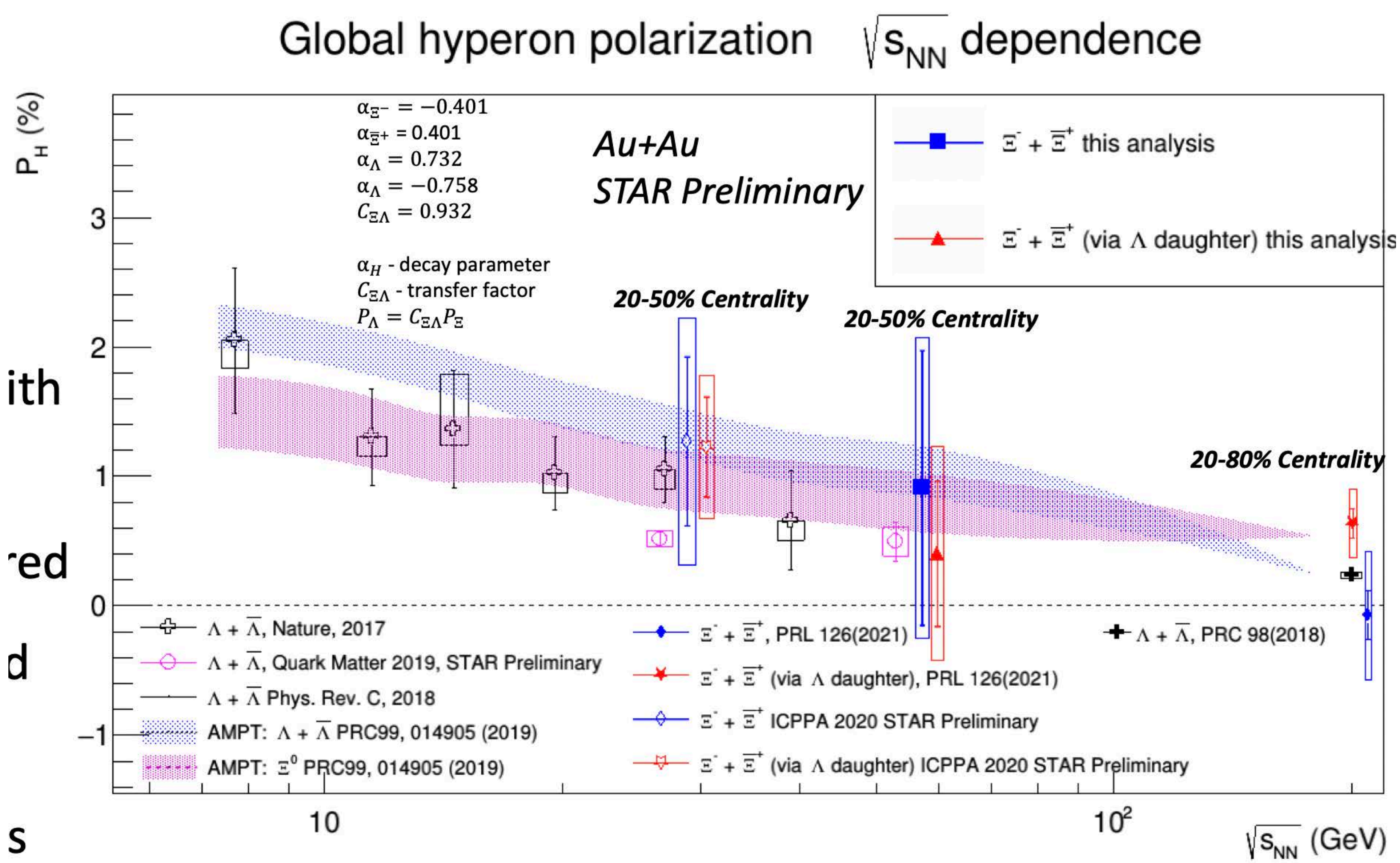
$$\langle P_\Xi \rangle = 0.47 \pm 0.10(\text{stat.}) \pm 0.23(\text{syst.})\ [\%]$$

$$\langle P_\Omega \rangle = 1.11 \pm 0.87(\text{stat.}) \pm 1.97(\text{syst.})\ [\%]$$

- Ξ and Ω polarization could be larger than that of Λ
- Consistent with AMPT model calculation within uncertainties.
- Naive expectation
  - Lighter particles could be more polarized (Ξ<Λ)
  - Earlier freeze-out leads to larger polarization (Ξ>Λ)
  - Feed-down effect : ~15-20% reduction for primary Λ P_H

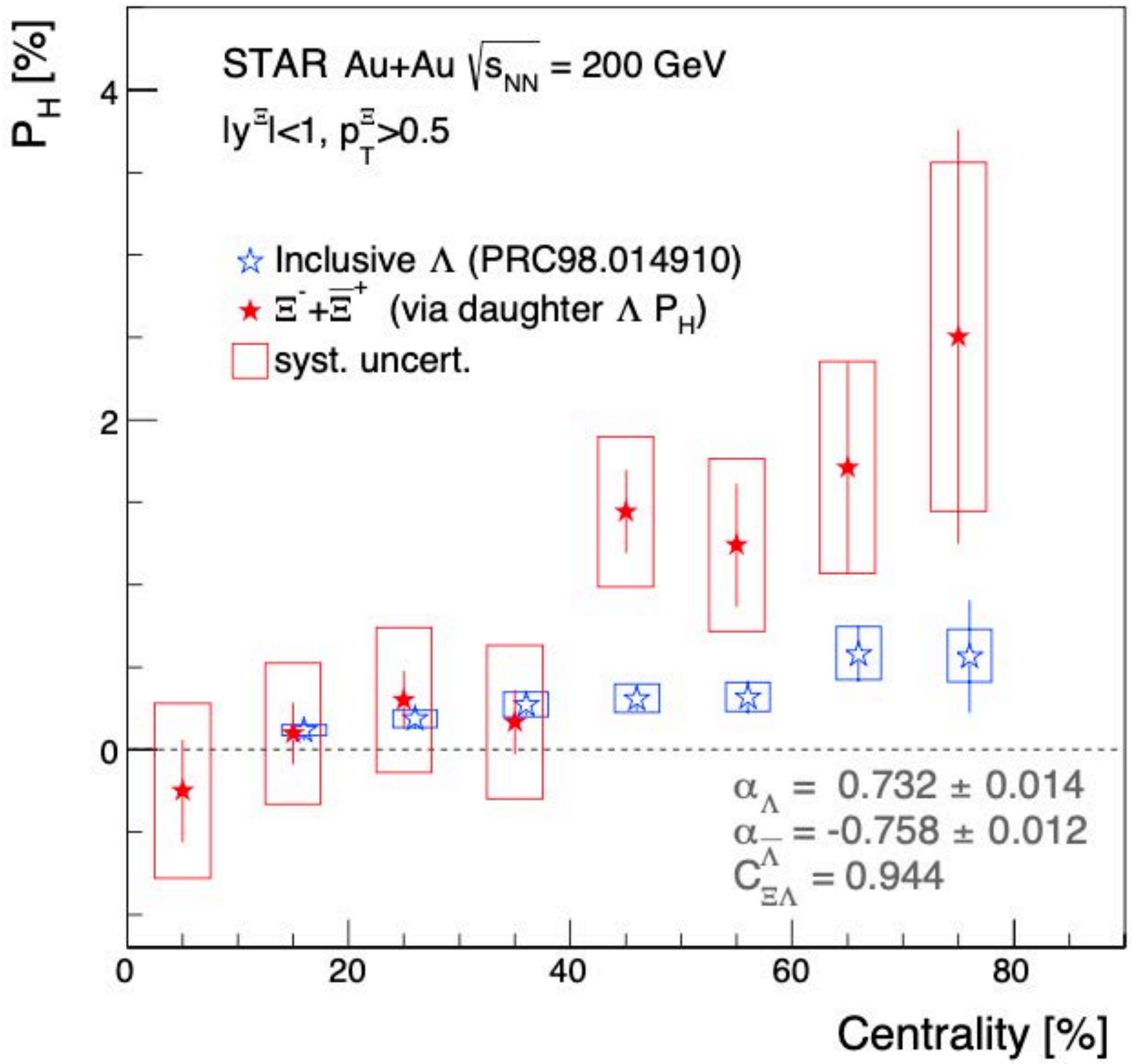
Ξ polarization at 27 and 54.4 GeV

- Global polarization have measured in Au+Au collisions at 27 and 54.4 GeV
  - Consistent with AMPT model within uncertainties
  - Ξ polarization is consistent with Λ polarization within uncertainties.



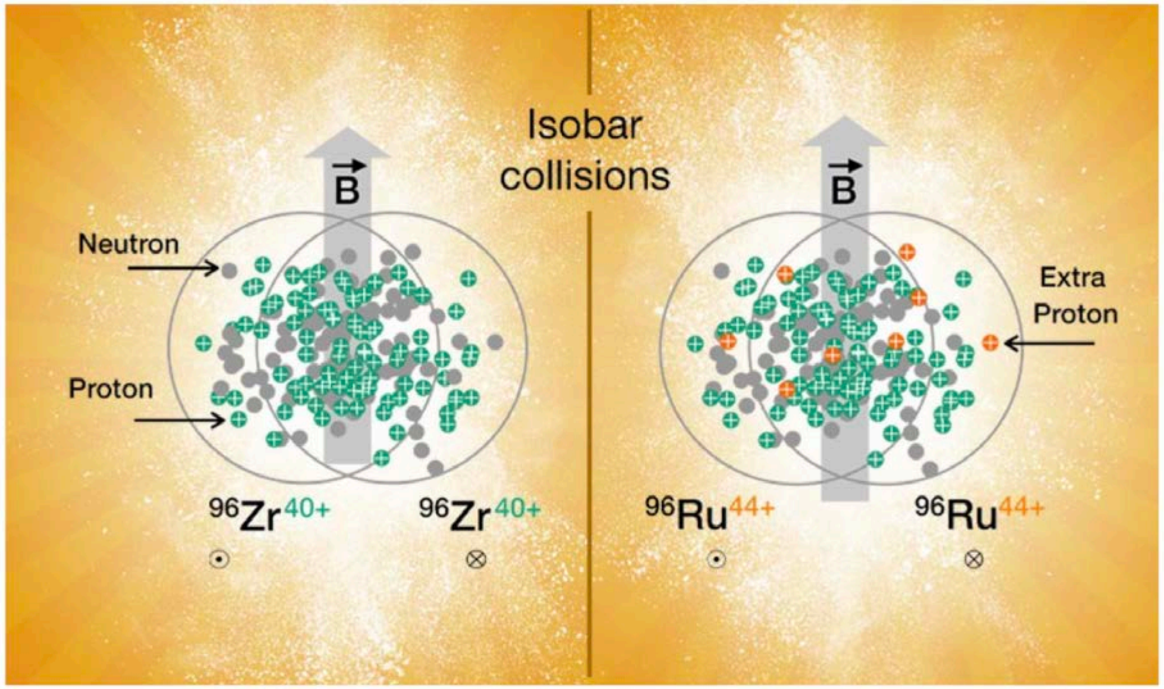
Centrality dependence of Ξ polarization

J, Adam et al. (STAR), PRL126, 162301 (2021)



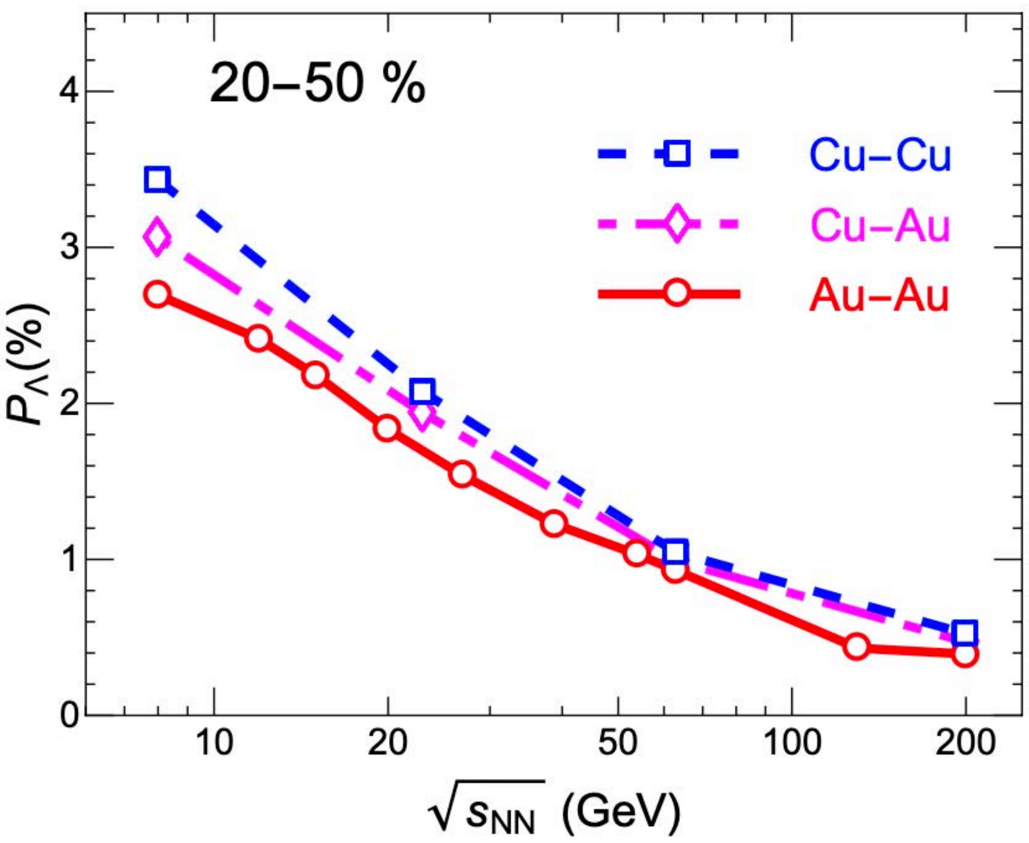
- Ξ polarization increases in more central collisions as well as Λ polarization.
- Ξ polarization could be larger in peripheral collisions.

Global polarization in isobar collisions



- Global polarization in Zr+Zr and Ru+Ru
  - The mass number is the same but the proton number is different.
  - Initial magnetic field different (~10%)
  - Verification of the magnetic contribution

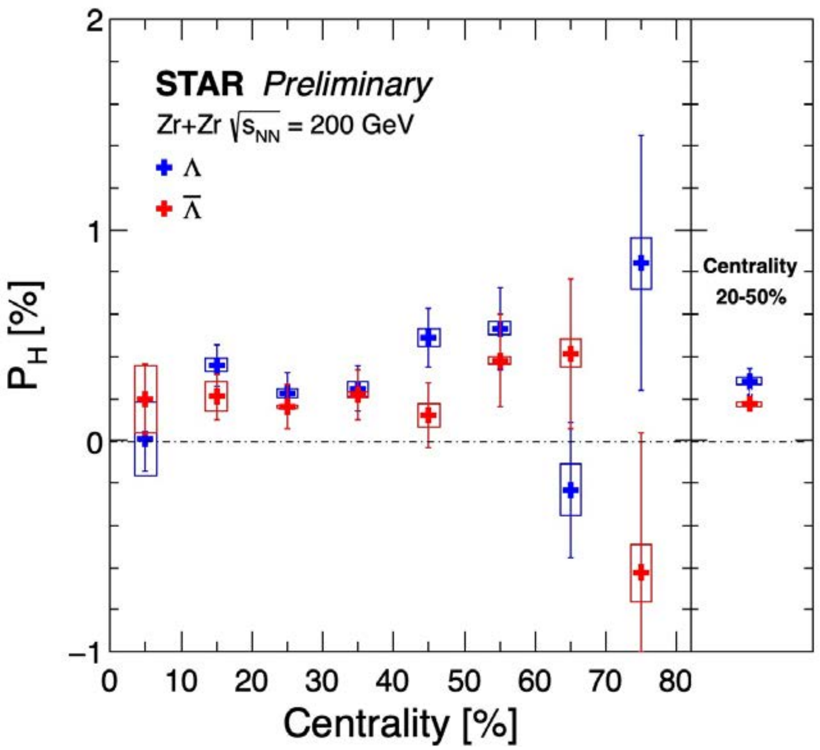
S. Shuzhe et al., *Phys.Lett.B* 788 (2019) 409–413

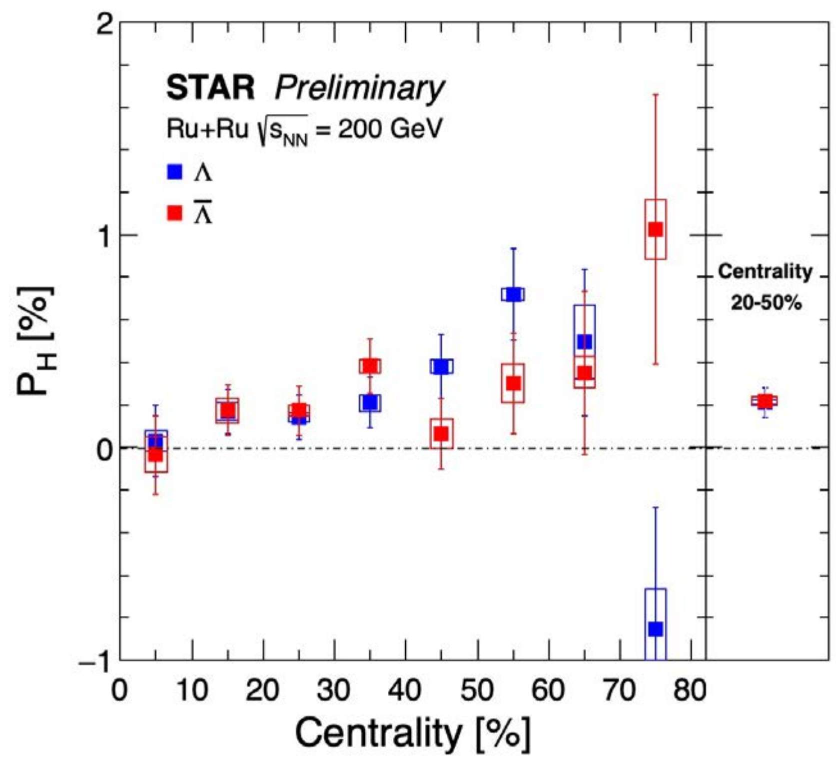


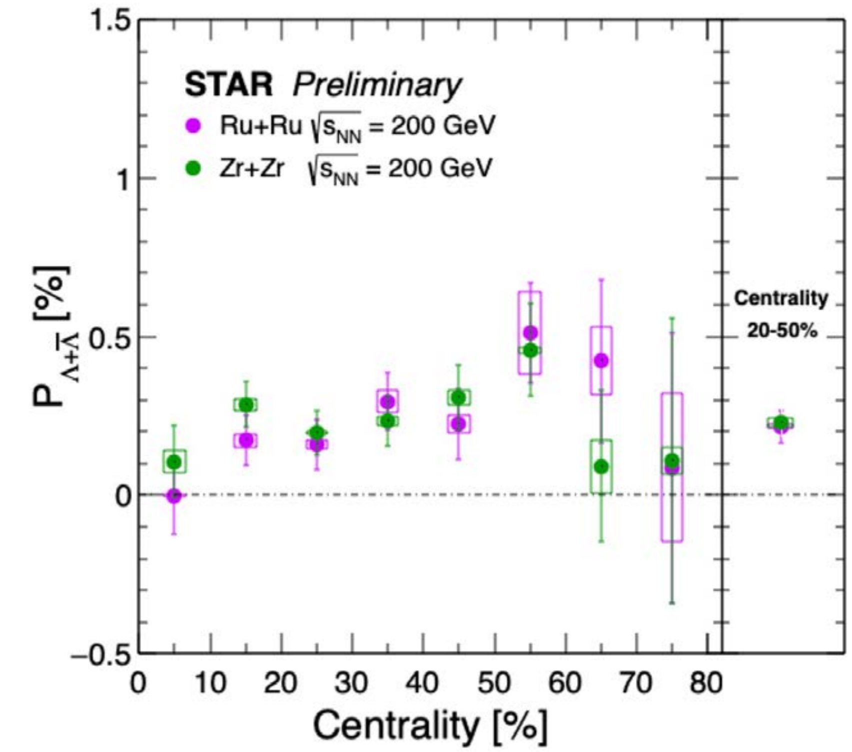
- System size dependence of the P_H
  - AMPT model expects global polarization is larger in Cu+Cu than Au+Au collisions.
  - The timing of the Λ production depends on the collision system. (Cu+Cu < Cu+Au < Au+Au)

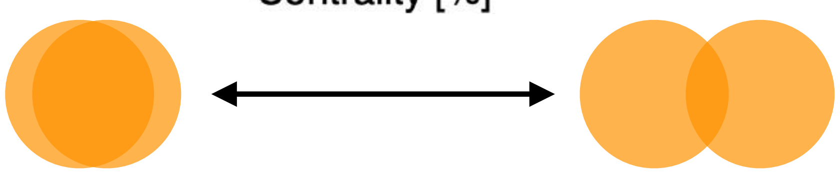
Global polarization in isobar collisions

Global polarization of $\Lambda(\bar{\Lambda})$ hyperons in Au+Au collisions at 200 GeV



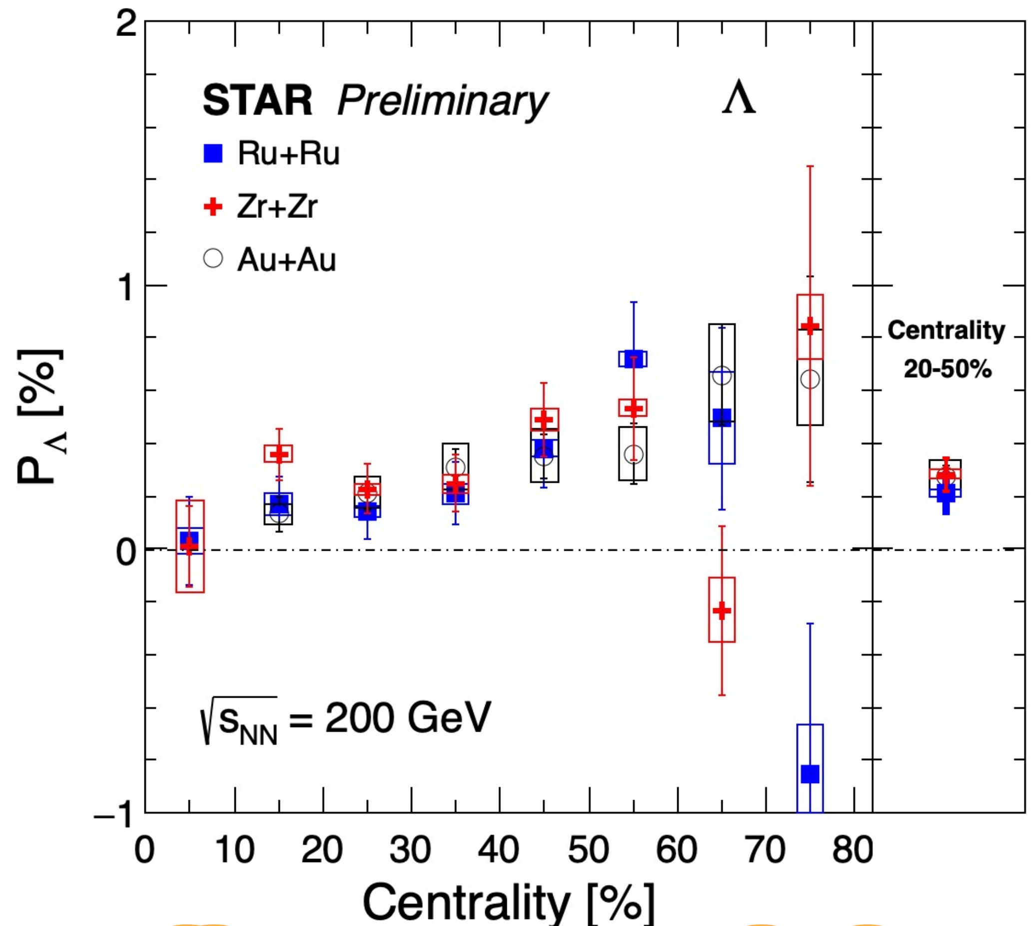


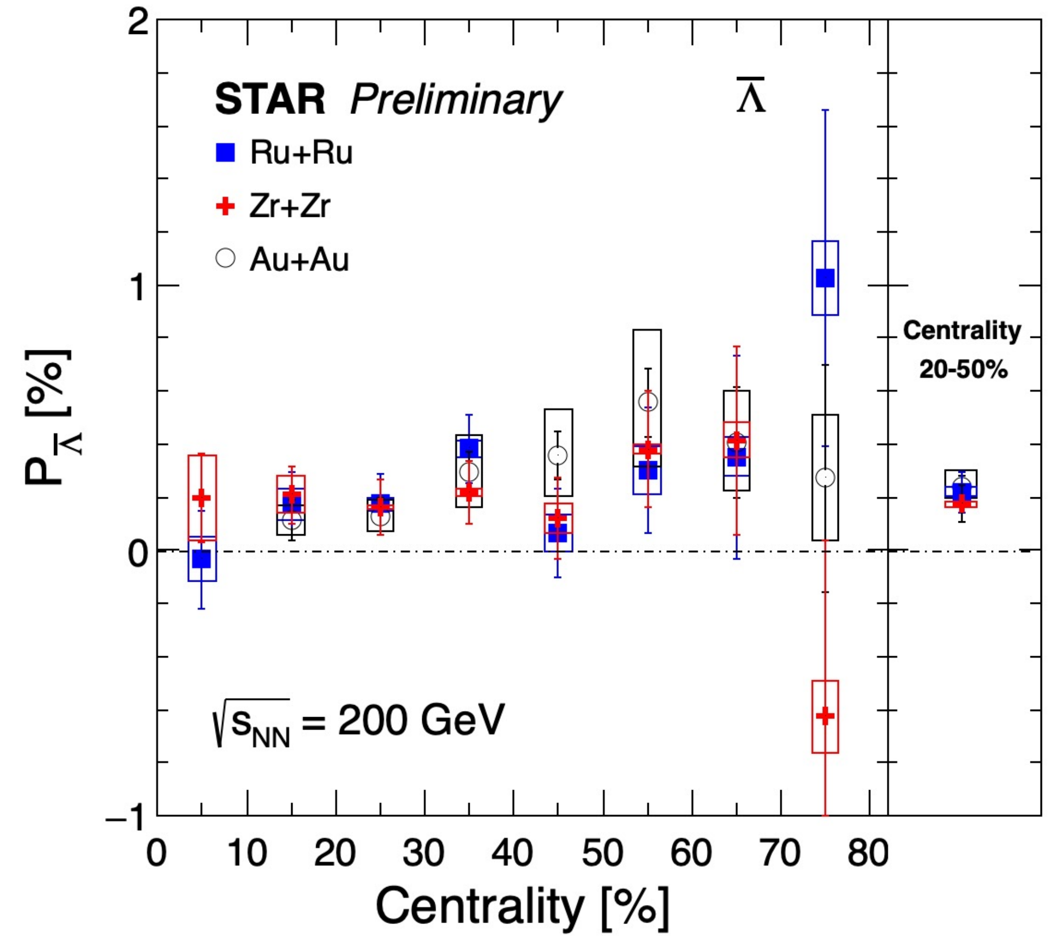


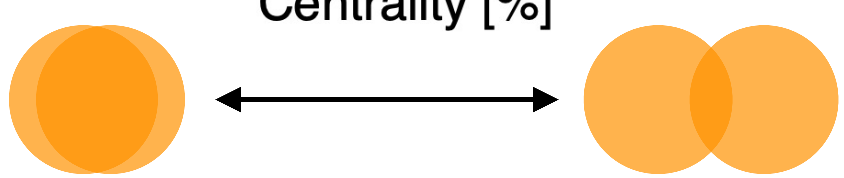


- Significant global polarization are observed, P_Λ and $P_{\bar{\Lambda}}$ increase with centrality.
- No significant difference between P_Λ and $P_{\bar{\Lambda}}$ in Ru+Ru and Zr+Zr collisions.
- $P_{\Lambda+\bar{\Lambda}}$ are consistent between Ru+Ru and Zr+Zr collisions.

Comparison with isobar and Au+Au collisions







- Global polarization of Λ and $\bar{\Lambda}$ are consistent between isobar and Au+Au collision system, no collision system dependence is observed.

Polarization along the beam direction : P_z

- Stronger flow in in-plane than in out-of-plane cloud make local polarization along beam axis
- Longitudinal component, P_z, can be expressed with $\langle \cos\theta_p^* \rangle$

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_{\mathrm{H}} \mathbf{P_H} \cdot \mathbf{p}_p^*)$$

$$\langle \cos\theta_p^* \rangle = \int \frac{dN}{d\Omega^*} \cos\theta_p^* d\Omega^*$$

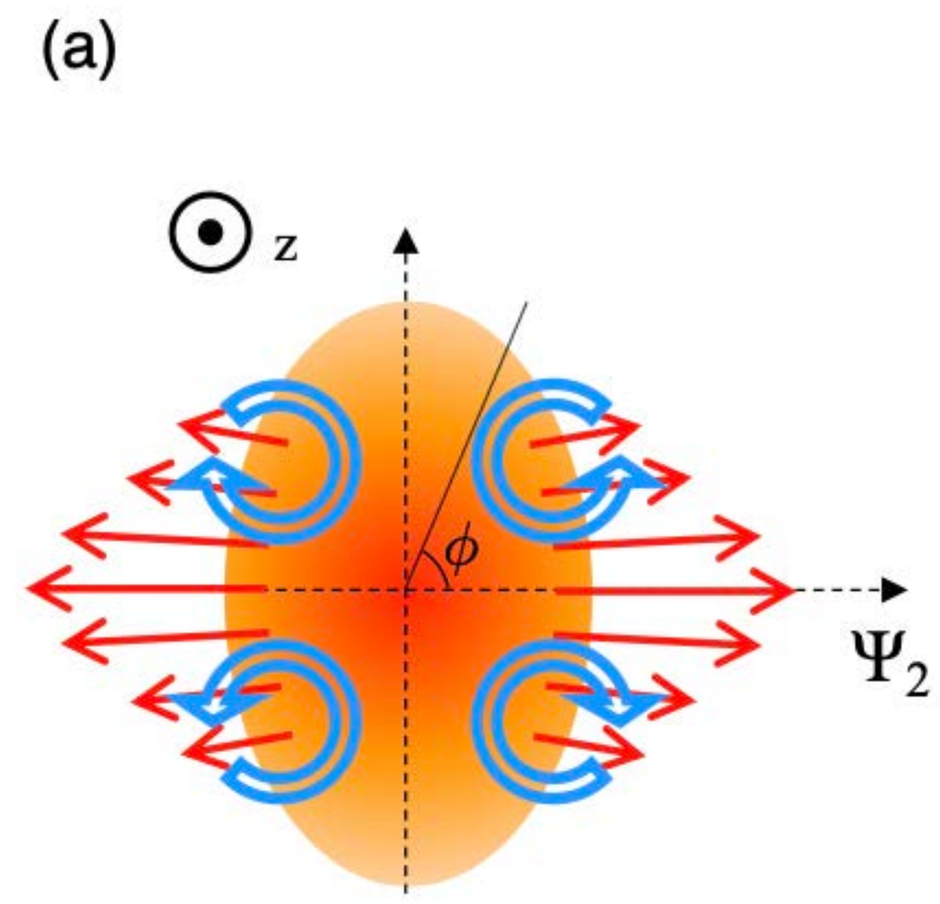
$$= \alpha_{\mathrm{H}} P_z \langle (\cos\theta_p^*)^2 \rangle$$

$$\therefore\ P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}} \langle (\cos\theta_p^*)^2 \rangle}$$

$$= \frac{3\langle \cos\theta_p^* \rangle}{\alpha_{\mathrm{H}}} \quad \text{(if perfect detector)}$$

α_H :decay parameter

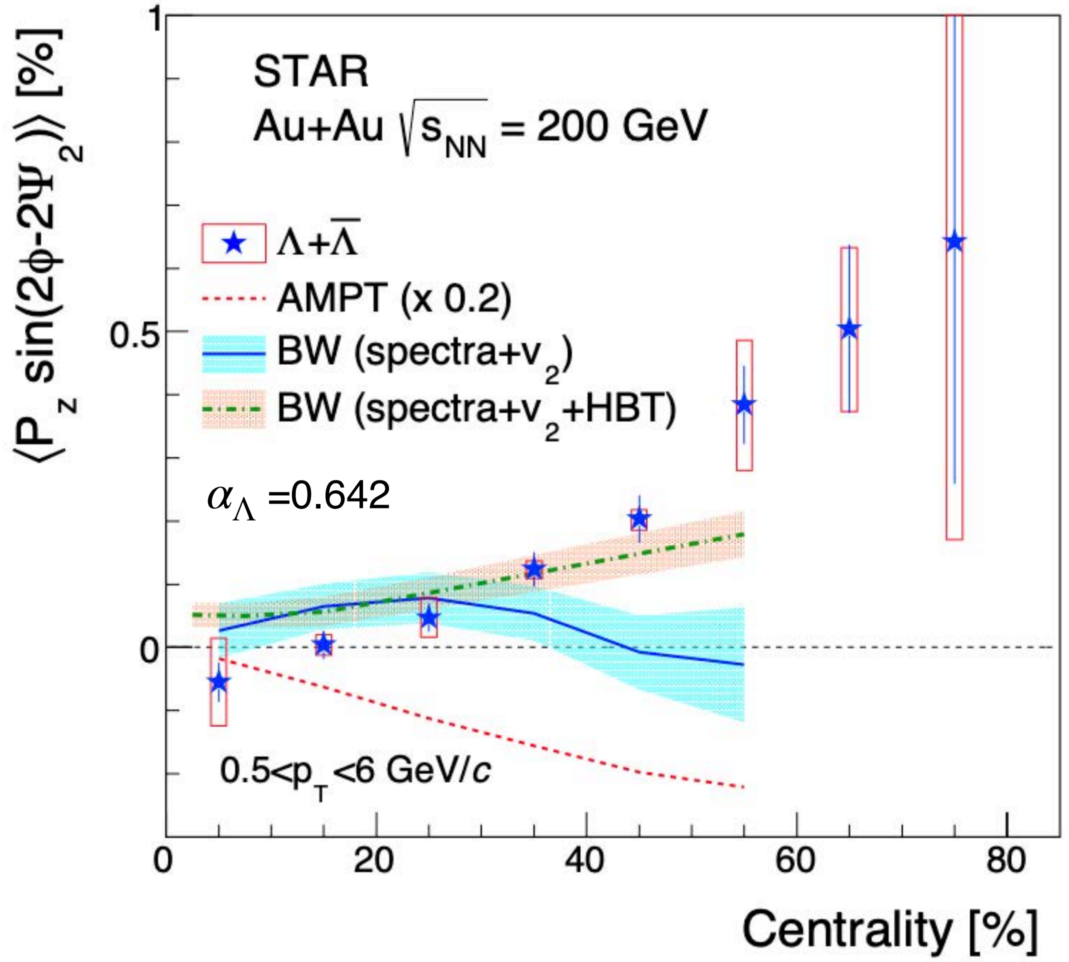
θ_p^*: θ of daughter proton in Λ rest frame

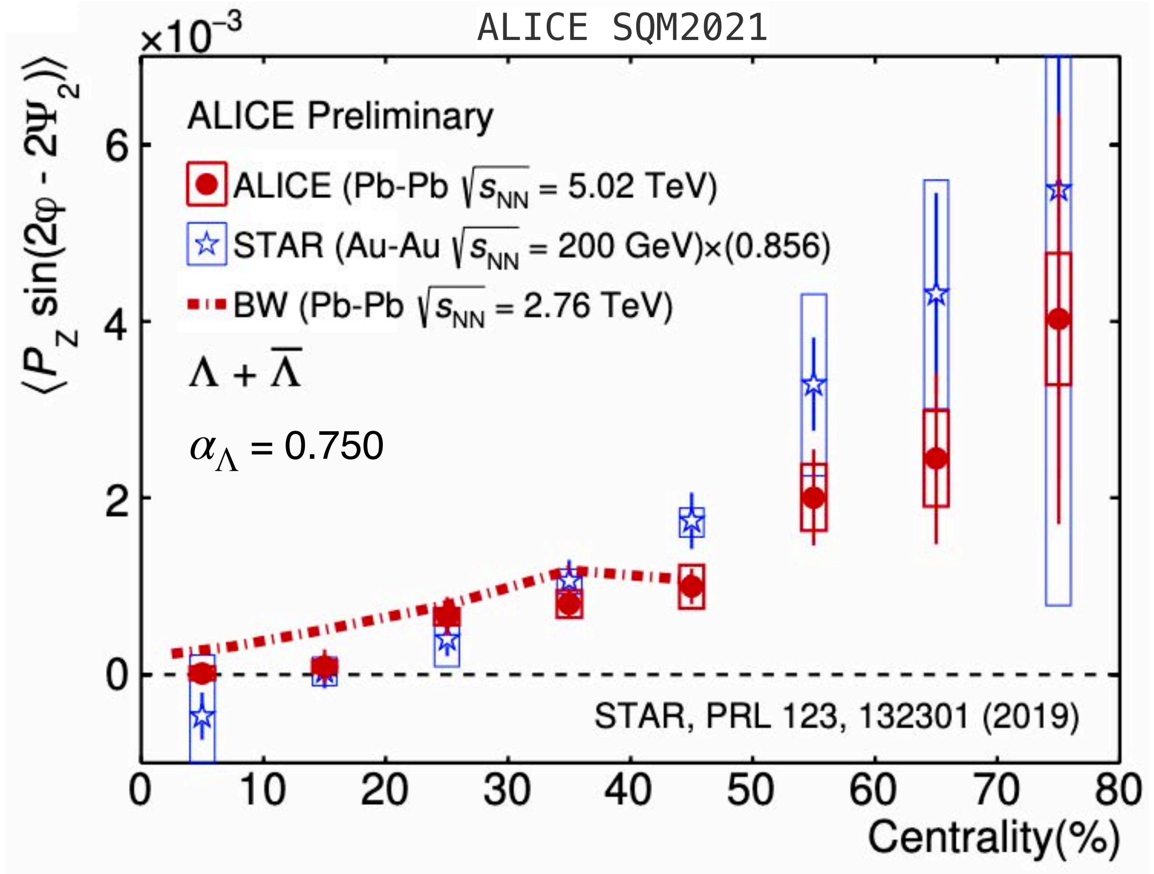


arXiv:2303.09074

Centrality dependence of P_z

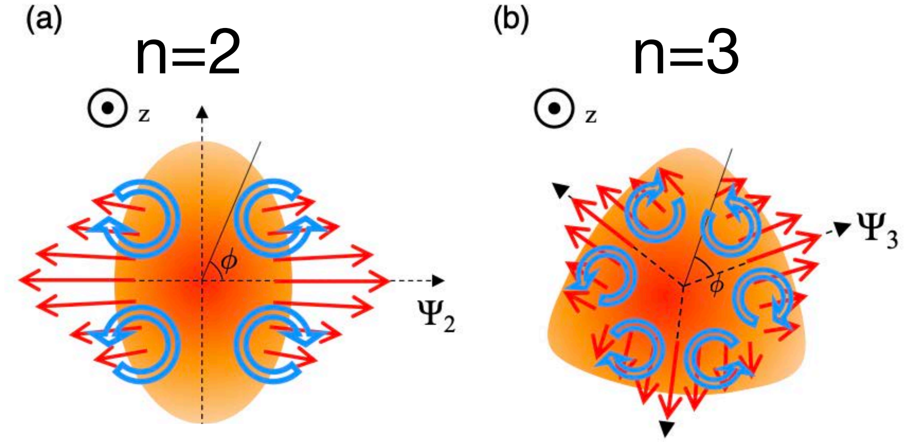
J, Adam et al. (STAR), PRL123, 132301 (2019)



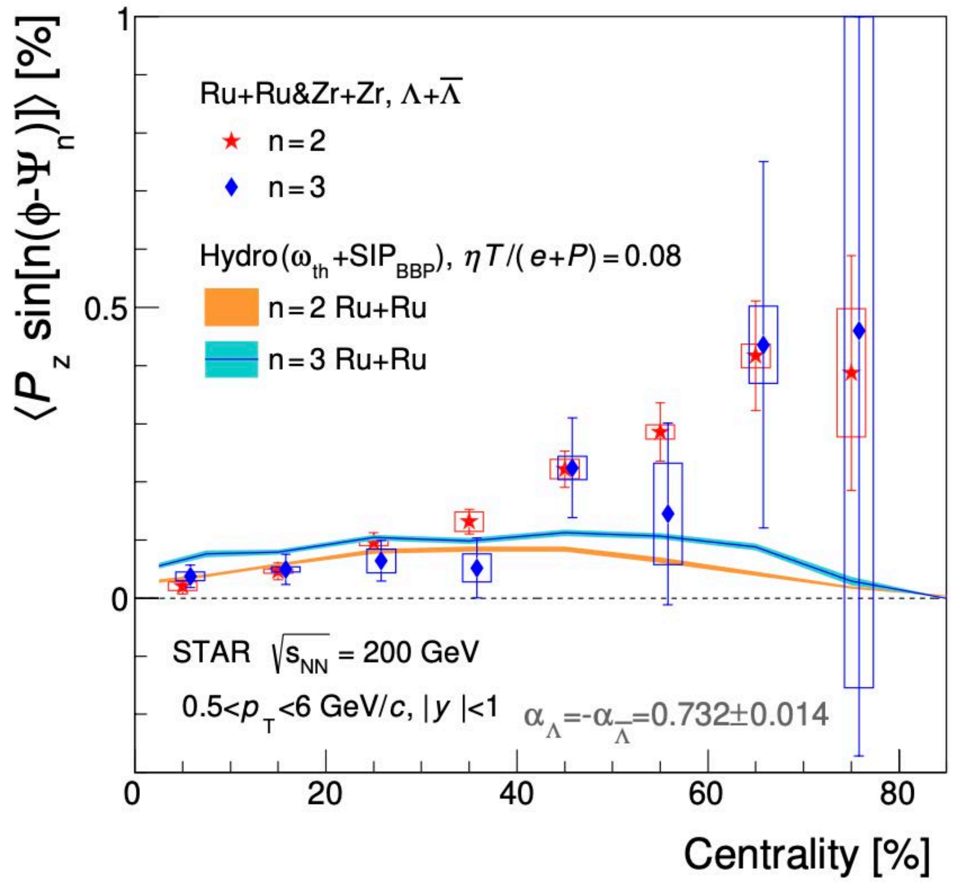


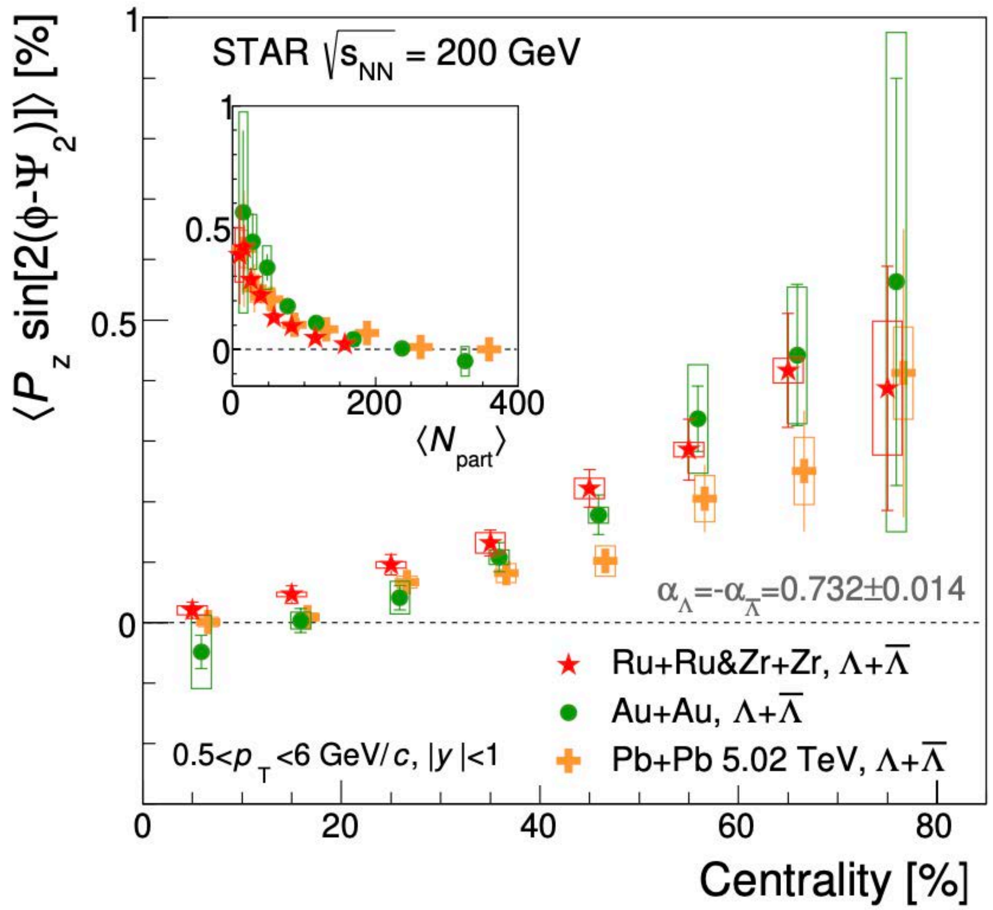
- **Local polarization is larger in peripheral collisions.**
  - v2 is large in peripheral collisions
  - v2 has finite values due to the initial density fluctuations in most central collisions but Pz is zero within the uncertainty.
  - Consistent with BW model but AMPT model predicts opposite trend

Centrality dependence of P_z



arXiv:2303.09074





- Hydrodynamic model with shear-induced contribution can describe the result

vorticity : $\omega_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho - \partial_\rho u_\sigma)$ shear : $\Xi_{\rho\sigma} = \frac{1}{2}(\partial_\sigma u_\rho + \partial_\rho u_\sigma)$

- No strong collision system and energy dependence
  - v_2 in 5.02 TeV Pb+Pb is ~60% larger than that in 200 GeV isobar

Summary and outlook

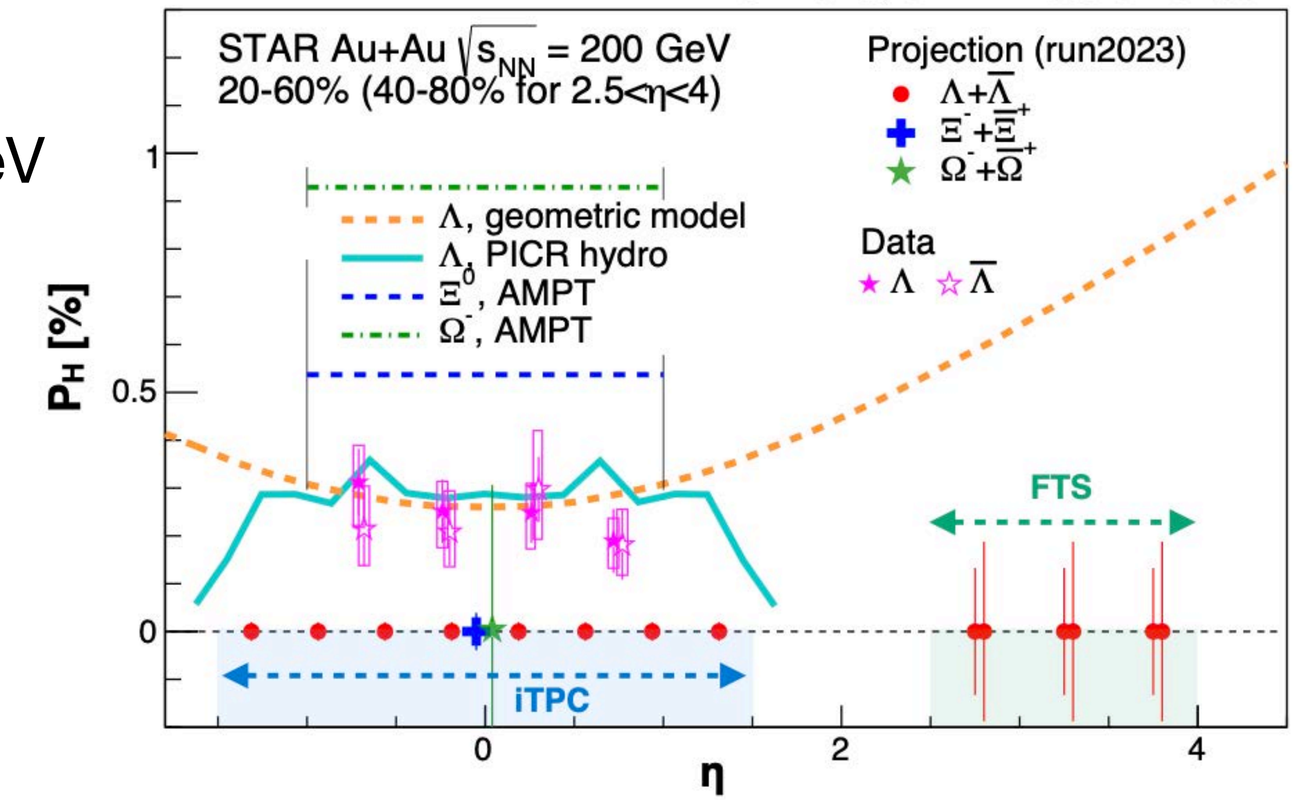
Summary

- Global and local polarization of hyperons has been observed in heavy-ion collisions
  - Most vortical fluid created in heavy-ion collisions ($\omega \sim 10^{21} s^{-1}$)
  - Differential dependence of global/local polarization has been measured
  - Ξ and Ω global polarization

Outlook

- High statistics data ob BES-II 7.7 - 19.6 GeV and FXT 3 - 7.7 GeV
- Polarization in large rapidity region can be explored in the future forward upgrade

BUR2020, STAR Note SN0755



Back up

Feed-down effect

✓観測されるΛ粒子のうち約60%が重い粒子の崩壊によって生成される。

✓親粒子の偏極は娘粒子(Λ粒子)に引き継がれる。

$$\mathbf{S}^*_\Lambda = C\mathbf{S}^*_R$$

C_{AB} : 粒子AからBへのスピン伝達係数

S_R : 親粒子のスピン

$f_{\Lambda R}$: ラムダ粒子のうち粒子Rの崩壊によって生成されるラムダ粒子の割合

μ_R : 粒子Rの磁気モーメント

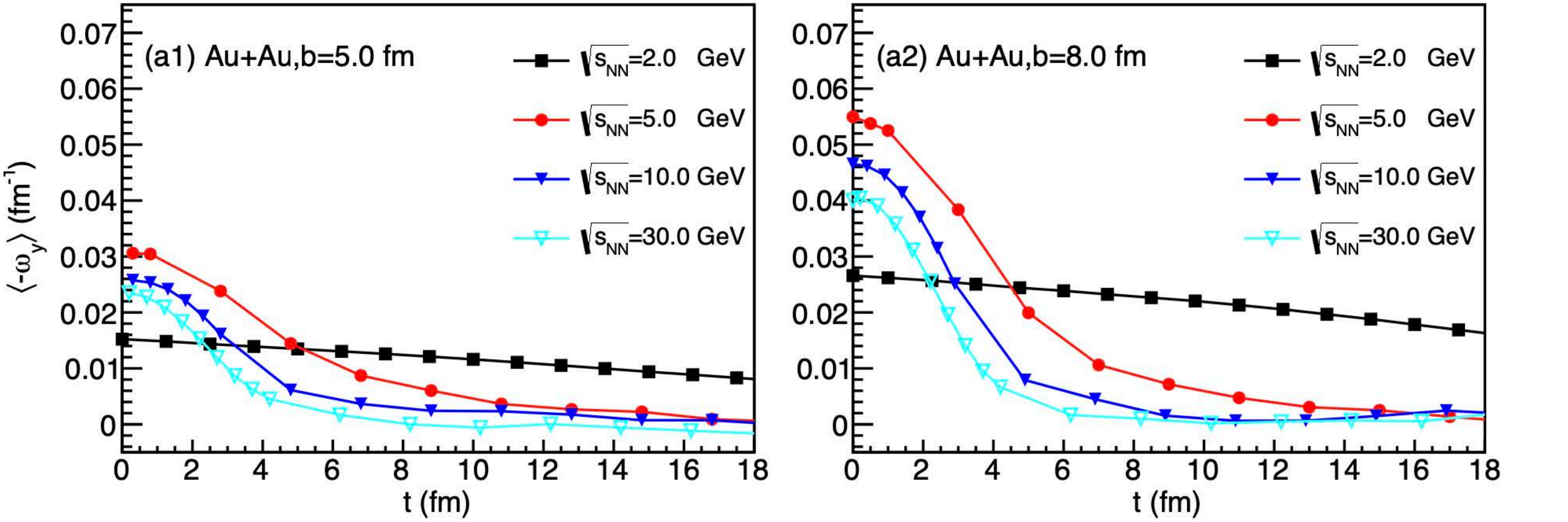
$$\begin{pmatrix} \varpi_c \\ \\ B_c/T \end{pmatrix} = \begin{bmatrix} \frac{2}{3}\sum\limits_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right) S_R(S_R+1) & \frac{2}{3}\sum\limits_R \left(f_{\Lambda R}C_{\Lambda R} - \frac{1}{3}f_{\Sigma^0 R}C_{\Sigma^0 R}\right) (S_R+1)\mu_R \\ \\ \frac{2}{3}\sum\limits_{\overline{R}} \left(f_{\overline{\Lambda R}}C_{\overline{\Lambda R}} - \frac{1}{3}f_{\overline{\Sigma^0}\overline{R}}C_{\overline{\Sigma^0}\overline{R}}\right) S_{\overline{R}}(S_{\overline{R}}+1) & \frac{2}{3}\sum\limits_{\overline{R}} \left(f_{\overline{\Lambda R}}C_{\overline{\Lambda R}} - \frac{1}{3}f_{\overline{\Sigma^0}\overline{R}}C_{\overline{\Sigma^0}\overline{R}}\right) (S_{\overline{R}}+1)\mu_{\overline{R}} \end{bmatrix}^{-1} \begin{pmatrix} P_\Lambda^{\mathrm{meas}} \\ \\ P_{\overline{\Lambda}}^{\mathrm{meas}} \end{pmatrix}.$$

Decay	C
parity-conserving: $1/2^+ \to 1/2^+\ 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+\ 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+\ 0^-$	$1/3$
parity-conserving: $3/2^- \to 1/2^+\ 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	$+0.900$
$\Xi^- \to \Lambda + \pi^-$	$+0.927$
$\Sigma^0 \to \Lambda + \gamma$	-1/3

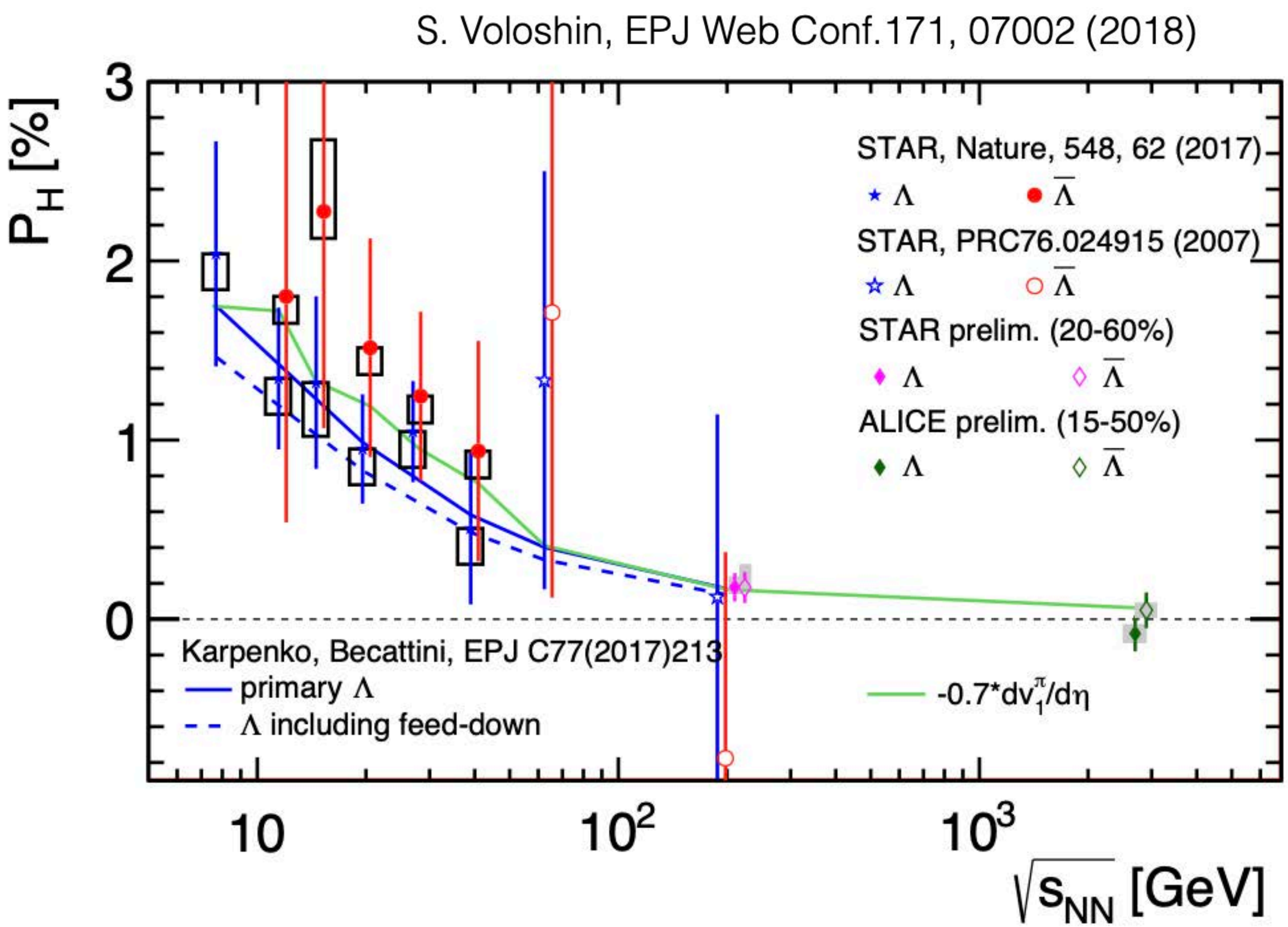
✓**ラムダ粒子のグローバル偏極は15 - 20 %程度抑制される。**

Time dependence of vorticity

X.-G. Deng et al., PRC101.064908 (2020)



Vorticity and directed flow



✓The slope of the directed flow at mid-rapidity is likely correlated with the vorticity.

- Global polarization and the negative slope of directed flow of pions have a similar collision energy dependence.